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Solving a locational distribution problem of non-toxic solid waste on the island of Puerto Rico

Sandra A. Soto
Louisiana State University and Agricultural and Mechanical College, ssoto2@lsu.edu

SOLVING A LOCATIONAL DISTRIBUTION PROBLEM OF NON-TOXIC SOLID WASTE ON THE ISLAND OF PUERTO RICO

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1995 Plan regional de infraestructura para el reciclaje y disposición de los desperdicios sólidos de Puerto Rico. [Regional Infrastructure Plan for Recycling and Disposal of the Solid Waste in Puerto Rico]. 1995. Mater Plan that stated the Solid Waste Management Authority's public policy and management proposals.

GIS Geographic Information Systems

LA Location-allocation

MRF(s) Material Recovery Facility

MSW Municipal Solid Waste

RCRA Resource Conservation and Recovery Act

ADS Autoridad de Desperdicios Sólidos (Solid Waste Management Authority)

ABSTRACT

The island of Puerto Rico is confronting a crisis in waste management due to inadequate management from the local government, the decreasing number of landfills available, high population density, and paucity of places for waste disposal. This research develops a least-cost model for the disposal and transportation of non-hazardous solid waste. Location-allocation (LA) and Geographic Information Systems (GIS) software are used to analyze the efficiency of the present pattern of waste allocation and to identify a near-to-optimal assignment of waste for the landfills in operation today and the landfills that will be open by 2008. The "near-to-optimal" models obtained from the LA analysis are compared to a regional system that has been proposed by the Autoridad de Desperdicios Sólidos (ADS) for the management of waste and with other waste-related infrastructure.

The LA analysis revealed that the present allocation of waste is not efficiently distributed. The total cost of the present allocation of waste is 99,011.5 tons (miles) per day, while the least-cost model cost would be 83,201.5 (tons) miles per day. The least-cost model for 2008 allocated only seventy-two of the seventy-six municipios on the main island, leaving highly populated regions and 2,207.5 tons of waste generated per day out of the analysis. Most of the waste coming from the northeast would be transported to Humacao's landfill (east). These results appear to be more economically efficient than other scenarios considered by the ADS. By 2008 most of the regions will be facing greater demands than landfill capacity. The scenario that presents the biggest savings is the LA model with twenty-seven landfills, while the model developed for 2008 provides better results than predicted by ADS, but the total distances values and cost are

higher than the other scenarios evaluated. This suggests that more landfills might be needed by 2008 in order to save in operating costs. Based on these results recommendations are posed in relation to the location of waste-related infrastructure and possible regional make-ups, among others.

CHAPTER ONE

INTRODUCTION

Waste management is a problem for most countries around the world because of the increasing volume of waste material and the paucity of places to deposit it. The island of Puerto Rico faces this problem with its increasing levels of waste generation and a reduction in the number of disposal facilities. As defined by the Resource Conservation and Recovery Act (RCRA), waste can be garbage, or any other residue such as mud, some liquids, solids, semi-solids, and gaseous material. According to the "Environmental Regulatory Glossary" solid waste is:

> Any garbage, refuse, sludge from a waste treatment plant, water supply treatment plant, or air pollution control facility and other discarded material, including solid, liquid, semisolid, or contained gaseous material resulting from industrial, commercial, mining, and agricultural operations, and from community activities, but does not include solid or dissolved material in domestic sewage… (Sullivan 1993, 519)

Hazardous waste, while beyond the scope of this research is defined by the U. S. Environmental Protection Agency as any substance that has specific levels of corrosivity, reactivity, inflammability, and toxicity (ADS 2003, np). It is solid waste that if not managed properly poses a threat to human beings or the environment due to its physical, biological, or chemical characteristics (Cutter 1993, 114).

In the archipelago of Puerto Rico, there are twenty-nine operating municipal landfills that receive non-hazardous refuse from households, business, and industries. There is an industrial landfill in the municipio of Peñuelas, which receives potentially hazardous and regulated medical refuse; and there is also a landfill in the municipio of Aguadilla, which is temporarily closed. This research deals with the twenty-seven non-hazardous landfills located on the main island of Puerto Rico.

Puerto Rico is the smallest of the Greater Antilles of the Caribbean. It is an archipelago composed of the main island, other smaller islands, and the keys and coral reefs that surround it. The main island has seventy-six municipios, and there are two more made of the offshore islands of Vieques and Culebra (Map 1.1). Municipios are the "primary legal divisions of Puerto Rico" that are treated by local and federal agencies, including the U.S. Census Bureau, as the equivalent of the United States' counties (U.S. Census Bureau 2004). The present landfills in operation are distributed throughout twenty-nine municipios on the main island and in Vieques and Culebra (Map 1.2).

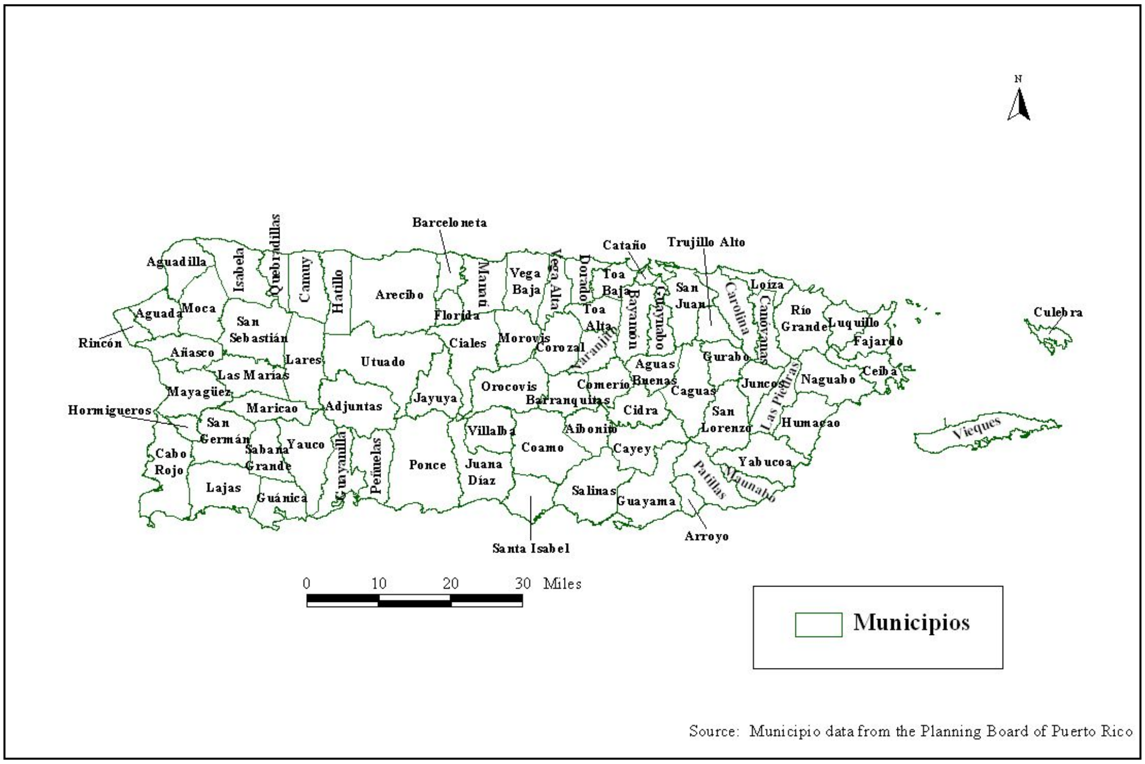
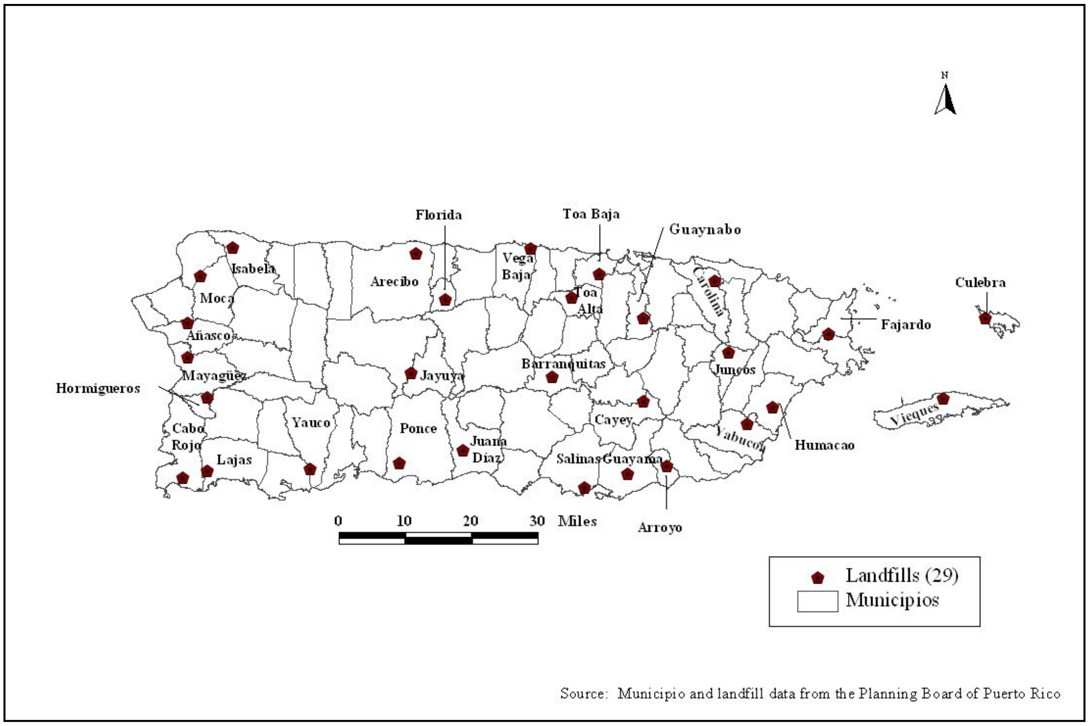


Figure 1.1 Municipios of Puerto Rico

Puerto Rico presents high population density and high levels of consumerism. In addition, its small territory is highly urbanized. This is why it lacks adequate spaces for waste disposal. The northern littoral of the main island of Puerto Rico is a karst zone, and in it there are nine landfills in operation today. In the northeast there is the San Juan



Landfill Location

1. Añasco
2. Arecibo
3. Arroyo
4. Barranquitas
5. Cabo Rojo
6. Carolina
7. Cayey
8. Culebra
9. Fajardo
10. Florida
11. Guayama
12. Guaynabo
13. Hormigueros
14. Humacao
15. Isabela
16. Jayuya
17. Juana Díaz
18. Juncos
19. Lajas
20. Mayagüez
21. Moca
22. Ponce
23. Salinas
24. Toa Alta
25. Toa Baja
26. Vega Baja
27. Vieques
28. Yabucoa
29. Yauco

Figure 1.2 Present Location of Landfills in Puerto Rico (2003)

Metropolitan Zone. It is the largest urban, industrial, and most populated region of the island. This area holds about 1.2 of the 3.8 million people that live on the whole island. It encompasses approximately eight (and a half) municipios and is Puerto Rico's largest waste producer. Most of the landfills in the northeast of Puerto Rico are going to be closed within five years. Therefore it is imperative to develop a least-cost model that would propose alternatives for waste material disposal at sites in the eastern, western, and southern portions of the territory.

In addition, the island's waste-related infrastructure poses a threat to the general population and the environment. About twenty-seven of the twenty-nine landfills in the island do not keep up with the local and federal environmental regulations. Many of these facilities experience constant fires, improper daily cover, inadequate fencing, improper entrances and exits for trucks, and lack of leachate and gas monitoring instrumentation. Some landfills are adjacent to communities. Others are located over sinkholes that replenish important underground water sources, are adjacent to superficial bodies of water, or occupy portions of forests and natural reserves. Moreover, environmental scientists have denounced that the landfills have received toxic or hazardous waste in the past (Fernández Colón 1988, 16). In addition to all these, the creation of illegal dumpsites is a common practice all over the island. It has even been carried out by some governmental entities.

Before 1970 solid waste was deposited in dumpsites and burned. Even though over time the government of Puerto Rico stopped burning its trash, most disposal sites were in violation of federal and local laws. This is why in 1994, greater restrictions of the U. S. Environmental Protection Agency's Resource Conservation and Recovery Act were put into effect, and about half of the dumpsites were closed (thirty-two of sixty-four). The remaining facilities received an allowance of five to seven years to meet the federal regulations. In most of the cases they have not met the standards.

On average, each person in Puerto Rico generates approximately 4.2 pounds of garbage per day. To deal with the increasing waste generation and declining landfill capacity, the government passed the Law Number 70 for the Reduction and Recycling of Solid Waste in Puerto Rico in 1992. It required industries and municipalities to recycle, and sought to reduce the amount of solid waste that ends up in the landfills by 35 percent. However, today only a 16 percent of reduction of waste has been achieved (ADS 2003, np). Another method proposed to help reach this goal was the establishment of new facilities for waste processing such as transfer stations, compost centers, and material recovery facilities. The government of the island was supposed to encourage the three R's: reduction of generation, reuse, and recycling.

Reduction is the process by which the consumption and production of goods are reduced, reducing the volume of solid waste produced. In this way, less material arrives at the landfills, extending their life expectancies (ADS nd, np). Reuse means to use more than once in order to save raw material, reduce energy consumption, and in that way conserve natural resources (ADS nd, np). This can be achieved by sharing products that are not constantly used and by trying to buy used products, among other examples. Recycling is to re-utilize materials that were discarded and could be re-fabricated and turned in to new products. Among the materials that could be recycled by the common citizen are aluminum, paper, cardboard, plastic, glass, oil, batteries, and tires.

Due to the lack of landfill space, the Autoridad de Desperdicios Sólidos (ADS), the island's agency in charge of managing and planning everything related to solid waste, has evaluated other methods and technologies for the processing and disposal of waste. For example, in 1995 the previous political administration proposed the establishment of two energy recovery plants (in Guaynabo and Arecibo), and since then, Material

Recovery Facilities (MRF), transfer stations (and mini transfer stations), and compost centers have been constructed and put to work through out different parts of the island.

This research will develop a least-cost model for the disposal and transportation of non-hazardous waste. Statistical methods such as location-allocation (LA) and Geographic Information Systems (GIS) software will be used to identify a near-to-optimal assignment of waste for the landfills in operation today, but with an emphasis on the landfills that will be open by 2008, which is five years from the date when this research commenced. The analysis carried out will prioritize the landfills because they are the main method of waste disposal on the island of Puerto Rico.

LA methods have been used for numerous studies that deal with practical issues and the public sector (Rushton 1988; Logan 1985; Thomas et al. 1991; Morrill 1976). In this light, LA will be used to answer two main questions: is the present pattern of waste allocation efficiently distributed? And what will be a near-to-optimal distribution of waste within five years, when most of the landfills will be closed? These methods are of great utility for this kind of research as they allow the researcher to evaluate the system taking into consideration various constraints. In this case, distance and supply and demand capacity are included. Even though, the results yielded are often not completely realistic they serve as a model to which the present systems aspire. As this research will show, there are also other waste disposal technologies and methods that will have to be considered, and their implementation encouraged with more success in order to save this archipelago from sinking in waste. After developing a better idea of an optimal assignment of flows of waste material according to the available disposal sites, this thesis will consider the whole system including other infrastructure. Finally, it will propose recommendations on possible regional needs for other landfills, transfer stations, MRFs, and compost centers. This research is a first step in a more comprehensive evaluation of the solid waste system of this island. The results and the recommendations proposed should be used to carry out other analyses using the same technical methods, but including more constraints. Later, the results obtained can be analyzed taking into consideration socio-economic, environmental, and physical characteristics of each region.

It is imperative that research like this is conducted to help this Caribbean nation manage its waste and resolve its solid waste crisis. This research will show the pertinent agencies that, as pressure groups have been arguing for decades, they can not continue to rely strictly on landfills for refuse disposal. The pertinent agencies can emulate part or all of the methods used in this research to develop the best alternative for waste redistribution and allocation, by using varied infrastructure. In addition, this research contributes to the extensive literature that exists on the geographic discipline on solid waste management.

CHAPTER TWO

LITERATURE REVIEW

Geography and the Environment

The current interest in environmental themes in the geographic discipline can be traced back to the decades of the 1960s and 1970s, predominantly in developed countries, when there was an increased environmental awareness, and citizens and members of the scientific community began to play a more active role in this respect (Turner 2002, 59; Jones 1983, 430). The environment and nature have always been core to the studies in this discipline, and current research has been influenced by works that can be traced back centuries. Over the years, the terms landscape, nature, and environment have been conceived in different ways, as has human interaction with these entities. An example of a scientist who had a profound influence in the discipline and in its practitioners that followed is Alexander von Humboldt, who dedicated most of his research to understanding how the unity of the landscape arose from such diverse phenomena (Turner 2002, 56). He also visualized human beings as agents of natural change, even though he thought that the influence that humans could exert on nature was weak (Martin and James 1993, 124-125). Other prominent geographers that have dealt with the results of the interaction between nature and humans include: Joachim Schouw (Denmark), Elisée Reclus (France), Alexander Ivanovich Woeikof (Rusia), and Peter Kropotkin (Russia) (Turner 2002, 56; Thomas 1955, xxviii).

Important American geographers that have also influenced the current studies in the environmental arena include William Morris Davis, George Perkins Marsh, and Carl O. Sauer. Davis, who was trained as a geologist, conceived man as an internal part of the landscape and as dependent on nature's resources for survival. This scholar made great contributions to geomorphology and to the development of geographical education in the U. S. (Martin and James 1993, 305-307). George Perkins Marsh, who lived in nineteenth century New England, stated his ideas about humans' influence on nature in his work "Man and Nature; or, Physical Geography as Modified by Human Action." As explained by William L. Thomas Jr., this work is "the first great work of synthesis in the modern period to examine in detail man's alteration of the face of the globe" (Thomas 1955, xxix). What makes this scholar so ahead of his time is his awareness of how humans could influence the earth, and how this could have an effect on our own subsistence. He proposes that humans develop a morally sound relationship with the Earth and its resources (Thomas 1955, xxix).

One of the earliest and seminal works of the past century within geographic academy that explores the topic of human agency and influence on the Earth is "Man's Role in Changing the Face of the Earth" (1955). It is a collection of works from an international-interdisciplinary symposium celebrated during the summer of 1955, which had as central topic "what man has been doing to and with his habitat" (Thomas 1955, xxi). One of this symposium's planner and most outstanding collaborators was the geographer Carl O. Sauer. This well known scholar has made great contributions to the area of historical geography, carried out studies on the origins of animal domestication and placed great emphasis on the influence that human beings can have on the environment that surrounds them (Turner 2002, 59; Martin and James 1993, 351). In the symposium's work he recounts human cultural development from a historical perspective by analyzing how nature influenced this development and human influence back on nature. He tackles topics such as: climatic changes and its effects on humans, the discovery of fire, man's nature, and how different periods of human's cultural development have influenced nature and how they have been influenced by it (Sauer 1955, 49-69). Abel Wolman, an engineer and stateman, also contributes to the work, discussing waste disposal practices and methods. While Wolman is not a geographer he carries out one of the first extensive analyses on waste management that takes place in a geographical forum. In his writing Abel Wolman does an analysis of the benefits and setbacks of diverse methods of refuse and human waste (sewage and drainage system) disposal that have been used in developed and under-developed countries. At the end of the essay he makes a more specific analysis of methods of waste disposal (such as landfilling) and recovery (or "waste salvage" as he calls it) (which includes separation of material taken from disposal sites and incineration), making an assessment of the pros and cons of each one. The author points out that composting, which has been practiced in eastern countries such as China and Japan, has potential, but has not been widely used in western countries because of technical and economical reasons (Wolman 1955, 813). It is important to point out the author's discussion of natural purification methods, such as lakes, rivers, and oceans, used during the nineteenth century for the processing and cleaning of sewage material. He explains that these methods fell out of favor because of the nuisance ("from odors, sludge deposits, oily surface, or objectionable physical appearance") that they caused to human beings (Wolman 1955, 809). This fact shows the anthrocentric way of thinking, and the absolute disregard in which humans - especially of that century - had towards nature. Use of this method was halted due to the nuisance that it was causing (only) to human beings, but not because of the probably devastating consequences that it was having on the environment and other species.

For this same period of the mid twentieth century, Gilbert F. White became an influential scholar. White's hazard studies introduced a new perspective to the studies on the environment. He worked on a variety of topics such as water supply, flood hazards, river basin planning, environmental perception, and arid zone development, among many others (Wescoat 1992, 587; White and Haas 1975, xviii). His belief that research was supposed to serve the public can be seen in his emphasis on policy development and in his activism in local and international organizations, such as his involvement in international panels to solve water conflicts in the Middle East (Turner 2002, 59; Wescoat 1992, 588).

In addition to hazards studies, other core topics covered by current environmental geography are locational issues, environmental equity (environmental racism or environmental justice), environmental policy development, and hazardous waste disposal and siting. All of these topics are interconnected in such a way that any research of environmental nature covers some of them simultaneously. Most environmental issues that arise are locational in nature. In many cases, a facility's siting is carried out in unequal ways that place a higher burden to groups of a certain ethnicity, race, or economic class (equity issues). For this and other reasons, specific groups such as minorities or low-income communities, in many instances, are at greater risk of suffering from environmental and technological hazards; and these conflicts lead to public opposition (locational issues). Finally, research that is carried out in all of the previous topics can and does have repercussions in the development of policies of environmental nature.

Locational conflict occurs when a locality opposes the siting of a facility near by them (Lake 1987, xv). This has come to be known as LULUs (locally unwanted land uses) (Popper 1985, 1). The players are often communities, local municipalities, or environmentalists who oppose corporations, industries or state or federal governments (Lake 1987, xvi). Polls have shown that the facilities more likely to be rejected by citizens are nuclear power plants and hazardous waste sites (Popper 1985, 5). On the other hand, these facilities have to be located somewhere and in many instances extreme environmental activism and constant community opposition to LULUs have played a crucial role in delaying, increasing costs, or completely blocking numerous projects, some considered essential (Popper 1985, 8). This issue is relevant to the topic of waste-related facilities' siting and management because no one wants them close to their home, but these sites are needed and have to be put somewhere.

Much research has been done in this area. Some examples include: Popper 1985; Lake 1987, Gladwin 1980, Kunreuther, Linnerooth, and Vaupel 1984, Bingham 1986, Flahaut, Laurent, and Thomas (2002), and Abrams and Primack 1980. For instance, Frank Popper (1985) discusses the causes for LULUs rejection, the environmentalist's job in avoiding the placement of these facilities, and the consequences of this conflict. Thomas Gladwin (1980) carried out an investigation in the chemical industry with the purpose of finding empirical and theoretical generalizations in regard to environmental disputes; their issues, actors, tactics employed, resolution mechanisms, and outcomes (Gladwin 1980, 15). The ultimate purpose of this research was to develop a theoretical background on the causes, course, and effective management of environmental conflict (16). He found that environmental conflicts are changing (to new targets) and spreading (geographically and into more types of industries) (19). There has been an increase in the number of issues involved in a conflict, with land use, social impact, and human health rising in importance (23). It was less common to solve disputes through legal actions in the 1990s, while governmental administrative actions and other resolution methods have risen (30, 34). There is a relation between the findings from this research and the waste management industry because when waste-related infrastructure is being placed near communities many issues that arise are also related to the impact that these facilities will have on land use (especially in the case of landfills), the impact on the real estate values and quality of life (from trucks, noise, etc.) (social impact), and to the fears that arise from the knowledge of past experiences that had profound effects on the human health.

Howard Kunreuther, Joanne Linnerooth, and James Vaupel (1984) evaluated how risk analysis and policy analysis can be used in the resolution of localtional issues that arise from siting potentially hazardous facilities. The authors also discuss elements that commonly arise in most of the siting controversies (261). In many cases conflicting interpretations of risk analyses arise because battling parties choose specific reports, or numbers and figures within each report to support their cause (267). This is why the authors propose the application of rules of evidence to risk analyses. First of all, this procedure treats risk analyses as incomplete evidence to the whole siting case, rather than final arguments (272). On the other hand, policy makers can help resolve conflicts by proposing programs that would benefit the opposing parties involved. This can be carried out by establishing compensation schemes that would be granted to affected groups (269-270).

Gail Bingham (1986) proposes mediation or the environmental dispute resolution approach to solve locational issues. The author argues that research has shown that about 78 percent of the time the parties involved have successfully reached a solution. In addition, since the participation in this process, unlike legal actions, is voluntary it is more likely that a decision reached is going to stick (Bingham 1986, 317-318).

Nancy E. Abrams and Joel R. Primack discuss the issues involved in the siting of a nuclear waste depository, and the reasons of and solutions to public opposition (1980). In addition, they propose a public participation model, using as example a Swedish case (Abrams and Primack 1980, 85). The main concern of the authors is that public participation is generally sought too soon or too late during the waste facility placement process (75-77). The citizens are not offered concrete issues to argue about, but vague technical questions (76). The authors explain that policy developed on public participation should not be general, instead it should specify that communities can choose whenever they think it is appropriate to be involved in the project development process (84-85).

Richard G. Kuhn (1998) also carries out an evaluation of citizens' perception of the siting of a nuclear-fuel waste disposal facility in Ontario, Canada. Since the federal Canadian government is evaluating the disposal of nuclear fuel waste in the Canadian Shield, Richard G. Kuhn carries out a survey in three northern Ontario communities to get a better grasp of the social and political elements that could block this project. The author found that the majority of respondents considered the facility's siting unacceptable due to high perceived risks to the health and security of the community. However, when offered incentives or compensations the respondents that considered the facility unacceptable decreased from 62 percent to 57.5 percent (23). The author found that the facility becomes increasingly unacceptable if located within a zone of 49.7 miles from the community. Finally, he finds that a regional rather than a community based approach will have to be carried out in order to increase the chances of siting of a nuclear-fuel waste facility because of possible opposition from near by communities (25).

Christian Uzo Okeke and Audrey Armour (2000) bring another angle to the studies of citizens' perception. They carry out a survey in the communities that surround the Halton landfill, in Ontario, Canada. The authors evaluate the perceptions of nearby residents who live close to a facility in operation, if their perceptions now have some influence by their opposition during the siting of the facility (or by the management of the facility now), what are the greatest concerns of the residents, and if this is influenced by distance from the site. The authors found that the residents' concerns had no relation to the issues raised during siting opposition. The two elements that raise the greatest concerns to the community are environmental and economic impacts from the facility; and when distance increased the degree of concern about the impact decreased (Okeke and Armour 2000, 147, 149).

In another study, Benoît Flahaut, Marie-Alexandre Laurent, and Isabelle Thomas use an extension of the basic p-media model of location-allocation (LA) to determine the optimal location of a recycling center in La Bruyère, Belgium. In this study the researchers want to minimize transportation costs (and increase accessibility to the facility), while decreasing the nuisance (noise) to the community. The optimal location was first located at a node (#15) which was very close to the population center. When the researchers increased the levels of nuisance slightly the optimal location was not influenced drastically away from the population. However, high extension/intensity of the nuisance pushed the facility farther away from the population center (Flahaut, Laurent, and Thomas 2002, 79).

Issues of environmental justice arise because many LULUs are established close to minorities, poor, sparsely populated, or politically underrepresented neighborhoods that do not have the economic resources to absorb its nuisance or political power to fight them off (Popper 1985, 1; Cutter 1993, 130). Environmental injustice also exists at the international level because:

> developing nations are ideal locations for dumping wastes-they have vast tracts of unused land, public opinion on the dangers is non-existent, and government authorities can either turn an unconcerned eye or be provided with sufficient monetary incentive to look the other way. (Cutter 1993, 139)

This is why geographic studies of environmental racism have focused on the spatial relationship between environmental hazards and community demographics in order to find out if the inequalities exist and to contribute to improved policy decisions (Pulido 2000, 12).

William Bowen et al. (1995) evaluates the relation between race, income, and toxic emissions in the city of Cleveland, Ohio (U.S.). The authors found high correlation between minority population concentration and toxic release amount at the county levels, but concluded that this is due to the coincidental location of these two variables in urban areas (Bowen et al. 1995, 656). At a smaller spatial scale the authors found a correlation between income and toxic facilities (657). Laura Pulido (2000) evaluates the traditional conception of racism, which she considers overtly narrow and restrictive, in order to explore other dimensions on the causes and process of environmental inequality. The author's goal is to consider the larger sociospatial process of inequality that produces racism, by looking at the process of urban and industrial development and the possible racist patterns by which it evolved, rather than focusing on issues such as siting, intentionality, and scale (Pulido 2000, 13-14, 33). Pulido's article is a critique of studies such as Bowen et al. (1995). Besides the works already presented, other articles mentioned here, such as Popper (1985), Cutter (1993), and Morell (1984), further explore the issues of environmental justice.

Craig Colten (2002) explores the processes and causes of racial segregation and environmental inequity in New Orleans, Louisiana, and the role played by the city's public work and the institution of the Jim Crow policies. In another study, Craig Colten (2001) discusses the conflict of environmental equity due to the placement of public housing development and an elementary school with a primarily poor African American population. These were placed on portions of the grounds of a municipal landfill. Colten discusses the role played by the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), better known as Superfund, in solving the contamination problem of the area and in dealing with local opposition and community distrust on governmental institutions. There is community distrust in governmental agencies due to a flood of confusing and contradicting information that they received, coming from risk assessment and toxicologists' analyses, and the Superfund's site evaluation. Community division on how the remediation effort should be carried out has caused greater delays to the clean-up project. The case studied in this research, the closed Agriculture Street Landfill in New Orleans, Louisiana and the surrounding community, proves the fact that the use of negotiated settlements and community involvement does not always help simplify and accelerate the remediation efforts (Colten 2001, 19).

As stressed earlier, environmental geographic work also has the purpose of having some effect in policy making. Studies discussed here, such as Cutter (1993), Gladwin (1980), Abrams and Primack (1980), Popper (1985), Kunreuther, Linnerooth, and Vaupel (1984), Bingham (1986), Pulido (2000), Ward and Li (1993), Haynes and El-hakim (1979), and Colten (2001), among others, evaluate the effects existent policy has or the need of it, in relation to locational issues, risk to citizens, environmental equity, and waste management. For instance, Craig Colten (2001) evaluates the resolution methods used by CERCLA and their effectiveness in solving the contamination problems that a community faces. On the other hand, Laura Pulido's (2000) evaluation of environmental racism using Los Angeles as a case study concludes with a proposal to change the current policy, so regulations focus more on industrial zones and pollutions clusters, rather than facility siting and individual facility cases (Pulido 2000, 33). Other research in this area has been carried out by Gibbs and Healey (1997) and Liverman (1999).

In another study, Howard Stafford (1985) evaluated the effects that environmental policy has on the current and future locational decisions of large, multiplant manufacturing firms (227). Since the end of the 1960s various environmental policies have been passed by federal and state governments and have established stricter controls over location, construction, facility design, and operation of manufacturing plants (227). In addition, the established policy makes the permit acquisition process harder. This is why there has been a general belief that environmental policy might have been changing and influencing the locational industrial and market patterns across the U. S. However, this research found that the traditional location factors, such as markets, labor, and materials remain predominant, while environmental regulations were left as secondary factors (238).

Policy development is one of the main research interests to geographers who study hazards. Hazard studies commenced with the research of scholars such as Gilbert F. White, but were extended to include events that happen when human-made developments and technology are added to the variables of society and environment (Cutter 1993, 2). "Technological hazards are socially constructed … they are products of failures in technological devices or systems as well as failures in political, social, economic systems that govern the use of technology." They can range from chronic pollution to the melt down of a nuclear power plant (Cutter 1993, 9). Geographers have studied different kinds of technological hazards trying to asses the risk perception of citizens, their distribution (at different scales), equity issues, management alternatives, and policy development (Cutter 1993). This is why technological hazard studies also have had an effect on policy development in U.S. and other countries.

An example of a technological hazard that has some relation with this research is the effects that hazardous (or non hazardous) waste facilities have on society. This topic has been studied from different angles, such as the risks associated with facility siting and transport, their inequitable distribution over society, and citizens' perception (Cutter 1993, 12, 112). Hazardous waste is solid waste that has particular physical, biological, and chemical characteristics that causes or contributes to threats to human health or the environment, when improperly managed (Cutter 1993, 114). It is defined by the U. S. Environmental Protection Agency as any substance that has specific levels of corrosivity, reactivity, inflammability, and toxicity (ADS 2003, np; Cutter 1993, 115). Historically most of this type of waste was landfilled, but there has been a shift since the late twentieth century to resource recovery (Cutter 1993, 133).

As explained by Susan Cutter (1993), the greatest producer of hazardous waste in the world is U. S., while the greatest sources of this material are commercial/industrial processes and the military. However, within the U.S. military generators are concentrated in western and southern states (Cutter 1993, 126). In terms of commercial/industrial generators, the highest levels of generation come from southern states (Cutter 1993, 122). However, the greatest risk potential can be found in Rhode Island, Vermont, Pennsylvania, New Jersey, and Oregon (Cutter 1993, 122). Two other sources of risk from hazardous waste are management facilities and transportation accidents. These facilities are concentrated in the northeast and midwest (Cutter 1993, 122).

Other work done in this area was carried out by David Morell (1984), who proposes a relief to the waste crisis through a reevaluation of the waste management strategies based in the politics of equity (118). The proposed management strategies consist of waste treatment rather than dumping. It emphasizes on-site treatment of the material and proposes a plan of compensation for affected communities. In addition, it proposes simultaneous siting of new facilities in accordance with regional needs and with patterns of equity and emphasizes the commitment to reestablish credibility of the government and the industry (118). The author evaluates the most common causes for public opposition and proposes solutions (119-122). On the other hand, Lawrence McGlinn (2000) presents an evaluation of hazardous waste in the United States, the geography of generators and transportation, and the methods that citizens and government officials use to control its location and transportation (11). McGlinn found that over 70 percent of hazardous waste was generated along the U. S. Gulf Coast, and most of the greatest generators today treat or store their wastes on site (13, 15). The author presents a synthesis of international and local legislation that has been put into effect since the end of the 1980s to control the transport and shipment of hazardous material among countries and U. S. states.

Other studies on waste disposal and management include Colten (1991, 1994, and 2001), Ward and Li (1993), Haynes and El-hakim (1979), and Melosi (2000). Craig Colten (1994) presents the process of urban development and sprawl that occurred in the city of Chicago, Illinois, since the mid-nineteenth century and the key role played by urban refuse in it. Refuse was used to reclaim inhospitable land or to make alterations to the topography of the city (124). The author divides the city's development into three distinct phases which have parallels in the general process of urban growth. Each fits within a period of urban growth that was influenced by public health policy, technological capabilities, and local environmental conditions (124-125). In recent years, the nuisance of waste disposal has been transferred to rural areas, which has caused water pollution and yielded patches of unusable land (Colten 1994, 125).

Robert M. Ward and Jinan Li (1993) make an assessment of the waste disposal system of the city of Shangai (China), its waste generation patterns, principal disposal sites, governmental and public attitudes towards this issue, policy development on this respect, and the negative environmental consequences of improper management of disposal sites, especially in relation to water pollution. On the other hand, Kingsley E.

Haynes and Sherif M. El-Hakim (1979) explore the relationship between technology and environment in Cairo (Egypt). In addition, the authors discuss policy development consideration in relation to the needs of this region. A great part of the waste management system (including collection and disposal) of this city is carried out through unofficial channels by three social groups, the *rubabikya*, the Wahiya, and the Zabaline, who have well defined roles in the system (102). The authors argue that the "appropriate technology" for a region (or country) is the technological advances that are in agreement with local cultural and economic conditions (106).

Adam D. Read, Paul Phillips, and Guy Robinson (1998) carry out an evaluation of government and industry perception of waste disposal methods in the United Kingdom, with an emphasis on landfilling. As the authors explain, the use of landfills has been and continues to be the preferred disposal method in this country. Due to environmental awareness and discouraging life expectancy forecasts for these facilities, the government has begun to develop policy and promote the use of alternative methods, especially recycling. However, the shift to alternative methods and the response to the decreasing landfill availability has been slow (65). A survey carried out by the authors showed that government entities have more realistic visions about the present paucity of landfill disposal space available and are more likely to promote other methods of waste disposal than private disposal contractors.

Environmental geography has also dealt with issues of sustainable development (Hobson 2003; Friedberg 2001), land use changes (Buckley 1998), and pollution (Buckley 1998; Ward and Li 1993). From the original contributions to the ways of thinking on the relations of humans and the environment, to the era of great environmental activism that was partially represented by a resurgence of research in this arena, to current studies, environmental geography has shifted and grown according to the predominant paradigms and lines of scientific interest of the moment. Through all of this process researchers have explored questions in relation to the polarization between the human and physical sides of the discipline (Jones 1983, 431), the application capabilities of environmental research (Jones 1983, 432; Wescoat 1992, 588), and the intrinsic relation between historical environmental geography and environmental history (Williams 1994; Powell 1996; Colten 1998). This has led to reevaluations of the discipline's roles and changes in research focus. All of this has been done taking into consideration possible contributions to society, especially through the influence on policy making.

Location-Allocation

"Location-Allocation is the process of determining the best, or 'optimal,' location for one or more facilities so the service or good is accessible to the population in the most efficient manner" (Environmental Systems Research Institute, Inc. 2001). The models developed look to optimize efficiency by simultaneously determining the configuration of the facilities (location) and assigning a service or "good" to the facilities (allocation) (Environmental Systems Research Institute, Inc. 2001). In other words, LA can search for the optimal location of a central facility or determine an assignment of flows, so the total cost of operation of the system is minimized (Scott 1970, 95). This model can be applied to problems of centralized decision making, such as that of government agencies, or decentralized decision making, in which there is an absolute competition among various producers and consumers (other restrictions also apply) (Scott 1971, 1). In this research the centralized decision making applies because a government agency will be carrying out all the decisions in seeking out cost-minimizing solutions. This methodology has also been used to find optimal location or allocation of a service or "good" for industries and business (Cooper 1963; Kuehn and Hamburger 1963; Platzman and Bartholdi 1989; Osleeb and Cromley 1978; Marianov and Serra 1998 and 2001; Min and Melachrinoudis 2001), land use developments (Gilbert et al. 1985), rural bioenergy planning (Venema and Calamai 2003), the reorganization of government agencies and institutions (Morrill 1976; Tomas, Robson, and Nutter 1991; Rushton 1988), health care facility organization (Logan 1985; Rahman and Smith 2000), and to determine the distribution or allocation of solid waste and its facilities across a territory (Marks and Liebman 1971; Walker, Aquilina, and Schur 1974).

During the development of this procedure various heuristic methods, models, and algorithms have been proposed. Improvements to this methodology have primarily concentrated in efficacy, solution optimality, simplification of the equations involved, reduction of the total computation time, and increase of its application capabilities.

The LA procedure answers questions of locational conflict and flow assignment. Research in this area has been of core importance in the geographic discipline, and the central place theory of Christaller is seen as one of the most important predecessors (Beaumont 1987, 21; Rushton 1988, 97). According to John R. Beaumont (1987) "the simplest type of location-allocation problems is the Weber problem" (26), which consists of finding the most efficient location of central facilities (warehouses) in such a way that the total cost of all flows between the centers of raw material and the market locations (demand points) is a minimum (Scott 1970, 97; Ghosh and Rushton 1987, 1). Since its origins, this procedure was developed to deal with locational conflicts for industries. This would change in more recent time since the procedure has been applied to a wider range of topics (Gosh and Rushton 1987, 8).

The development of LA can be divided into a classical and contemporary phase (Ghosh and Rushton 1987, 2). During the classical phase the single supply facility problem of the Weber problem evolved into the p-median problem, in which the total weighted distance between a p number of uncapacitated supply centers and multiple demand points is minimized (Ghosh and Rushton 1987, 2; Beaumont 1987, 26). Uncapacitated supply centers do not have a fixed or established capacity amount because they can be adjusted according to the needs of the demand points (Hsieh and Tien 2004, 1018). On the other hand, capacitated supply facilities do have a fixed capacity (Hsieh and Tien 2004, 1018). As Avijit Gosh and Gerard Rushton (1987) explain, when dealing with multiple supply facilities, the research scope goes beyond finding the location of those facilities to determining the allocation of demand points to those centers (2). An example of research from the classical phase is the work of Leon Cooper (1963), who developed a heuristic method to determine the location of multiple sources using an alternating procedure (Beaumont 1987, 27). Alfred A. Kuehn and Michael J. Hamburger (1963) developed a heuristic program using the GREEDY algorithm (Ghosh and Rushton 1987, 3) and the bump and shift routine to find the optimal location of warehouses and a near to optimal distribution system (Kuehn and Hamburger 1963, 645, 656). These researchers visualize a heuristic program “as an approach to problem solving with the emphasis in working towards optimum solution procedures rather than optimum solutions” (Kuehn and Hamburger 1963, 644). The authors develop the heuristic program in order to reduce the average search for a solution   On the other hand, Allen J. Scott (1970) explains a heuristic program as a set of rules set for the solution of a problem that converge in the direction of optimality (111). The program developed by Kuehn and Hamburger (1963) adds warehouses to the network until increases in the total cost of the system are noticed. In the next step, the bump and shift routine consists of dropping and shifting the location of warehouses in order to determine further cost saving solutions for the system. Only small subsets of warehouses are evaluated in detail to determine further changes to the system (Kuehn and Hamburger 1963, 645).

Other heuristic approaches developed during the first phase of development of the LA method are linear programming and the branch-and-bound procedure. Allen J. Scott (1970) explains that with linear programming the locations of central facilities are already known, there is an unknown assignment of flows between supply and demand points (or regions), and the purpose is to minimize the total cost of commodity flow (97). This procedure is mostly used when employing integral variables, and when searching for integer solutions (Ghosh and Rushton 1987, 3; Church and Eaton 1987, 178). "This assumption means that, at optimality, the set of points served by any central facility will be served uniquely and entirely by that facility" (Scott 1970, 100). On the contrary, when employing fractional variables a branch-and-bound procedure can be used (Ghosh and Rushton 1987, 3).

Allen J. Scott (1971) presents a linear program to solve the transportation of a single homogeneous good inside an economic system. The algorithm developed consisted of supply centers (*n*), which are a set of geographically distinct points or regions which produce some commodity; demand points (*m*), which are a set of geographically distinct points or regions that consume the commodity; the supply capacity of each individual supply point (S_i, the supply capacity of the i^{th} source); the demand of each demand point (D_j, the total demand at the j^{th} destination); the unit cost of transportation of the commodity from any producer to any consumer (t_{ij}); and the magnitude of the total flow (x_{ij}) (Scott 1971, 1; Scott 1970, 96). These are the basic components of any LA problem.

In order to solve the transportation problem, or linear program, presented by Allen J. Scott (1971) the following function should be minimized:

$$Z = \sum_{i=1}^{n} \sum_{j=1}^{m} t_{ij} X_{ij}$$

Under the algorithm developed successive program improvements of calculated solutions are carried out in order to find the one closest to optimality.

Michael F. Goodchild and B. H. Massam (1969) used the classical transportation problem to delimit administrative regions in southern Ontario in such a way that administrative cost would be minimized (86). The purpose of their research was to minimize variation within each regional unit, while maximizing variation among different ones. The boundaries of each region were delimited as a function of the amount of population that had to be served by each center. The models were evaluated based on population, distance, and optimality indexes. At the study site the townships were used as the basic spatial units by governmental agencies (Goodchild and Massam 1969, 87). The researchers developed an interactive method to re-locate the centers and boundaries until the final location would be very close to optimal.

Richard Thomas, Brian Robson, and Richard Nutter (1991) used linear programming models to test the spatial efficiency of the County Courts that make up the Northern Circuit in England and Wales. Secondly, they used heuristic methods to assess the proposed reduction of court workload (by the government) by evaluating a reorganization of this workload to central facilities (40). The authors found that case workload was not proportional to the population of the area served by each court. In addition, the model identified the court locations that would be most vulnerable if the reorganization of the system were carried out based on distance minimization criteria. This vulnerable locations are positioned close to large courts (or that carry large caseloads), rather than locations close to dispersed rural courts (51).

Moving away from the simple transportation problem, Jeffrey P. Osleeb and Robert G. Cromley (1978) evaluated the location, distribution, sizes, and market areas of the Coca-Cola plants located in southwestern Ontario using a nonlinear mathematical program. The researchers found that this company made cost minimizing decisions in the location of their plants, but the same did not occur when determining the plant size.

In relation to the branch-and-bound procedure, Arshad M. Khan (1987) worked on a theoretical waste disposal system that included transfer stations as intermediate points. Using a branch-and-bound procedure, the model optimizes costs by trading off transportation expenses against the capital and operating costs of introducing transfer stations (Khan 1987, 31). This study only considers the steps of collection and transport. The factors of weight and volume reduction that occur at the transfer stations are included in the formula, as well as the earth-cover factor needed in the landfills for processed and unprocessed waste. When the program was run it presented the details of the optimal solution with a description of the selected facilities (Khan 1987, 36).

An extension to the simple linear distance minimizing problem is the *maxcover* model, used by Lisa Duvic to find the "optimal" site for a potential state park in the state of Louisiana, between the parishes of Baton Rouge and New Orleans. Rather than a minimum distance between a set of demand nodes to a supply center, this model tries to maximize the demand served within a specified time or distance from the supply facility (Duvic 1996, 35; Environmental Systems Research Institute, Inc. 2001). The second phase of this research consisted of a GIS analysis using the Intergraph software where the author looked for a location within a specific distance from the location yielded by the LA analysis that met certain physical and social criteria. It was found that the optimal site to locate the park was along the Petite Amite River, between Livingston and Ascension parishes.

Vladimir Marianov and Daniel Serra (1998) evaluated various maximal covering LA models with waiting time constraints for congested systems. As they explain the waiting time at a service center greatly determines the quality of the service provided (401). The models were developed, first, with one server per center, and then with one or more servers per service center. The computation of the models was presented utilizing the branch-and-bound procedure and heuristic methods.

During the contemporary phase of development of LA, the models developed tried to depict and understand the behavior of producers and consumers and tried to represent their environment more realistically (Ghosh and Rushton 1987, 5). In addition, the procedure was applied to a greater range of problems and topics (5). Examples of procedures developed during this period are the multiple objective and hierarchical models. Studies that used multiple objective procedures employed more than one objective or criteria to determine locational configurations (6). Kenneth Gilbert, David D. Holmes, and Richard E. Rosenthal (1985) used a multiple objective integer programming model to find the optimal tract of land to be developed. The objectives considered in the problem where cost, proximity to desirable and undesirable land features, and the shape of the area (1509). The program was tested for the selection of a residential development site in Norris, Tennessee. John Current and Samuel Ratick (1995) determine the transportation routes and locations of treatment or store facilities of hazardous materials taking in consideration objectives related to risk, equity, and cost (188). Since all of these objectives are in conflict, there will not be an optimal solution for all of them (189).

Hierarchical models are used in multileveled service systems. Examples of these are health facilities and solid waste management systems that contain a hierarchy of the systems provided (Church and Eaton 1987, 163). Moshe Eben-Chaime, Abraham Mehrez, and Gad Markovich (2002) evaluated the total cost of a distribution system that was structured hierarchically while the service centers were restricted to a straight line along the network. The investigators concluded that this kind of system yields higher costs, that is why its use would only be justified where the costs of the major channels were sufficiently high (469). Vladimir Marianov and Daniel Serra (2001) extended their analysis of congested systems by inserting them into hierarchically structured facilities that have various levels of service providers (195). They presented two hierarchical models in which these systems were applied; one sought to find a minimum number of servers and their locations, with standard time and distance, while the second model intended to cover the maximum number of demand possible (195). The heuristic method used to solve the models is HiQ-MCLP. Possible results are presented. Other hierarchical models have been used to determine the distribution and arrangement systems, such as banking facilities (Min and Melachrinoudis 2001) and solid waste management systems (Walker et al. 1974).

LA procedures have been employed in the solution of practical problems by many researchers, in many instances having an influence on decisions made by government agencies and the policy put in effect in the region. This procedure has also been used in the development of service systems and the configuration of services in developing countries (Rushton 1988). For instance, Bernard I. Logan (1985) analyzed the proposed distribution of health care facilities in Sierra Leone, Africa; Richard Thomas, Brian Robson, and Richard Nutter (1991) assessed the distribution of Northern Circuit county courts in England and Wales; and Richard L. Morrill (1976) compared the proposed redistribution of legislatives and congressional districts in the state of Washington with the ones yielded from a capacity constrained LA model. Concerning solid waste management, David H. Marks and Jon C. Liebman (1971) searched for the "optimal" location of transfer stations and their effect in a system of transshipment network where additional constraints and parameters applied. This model was applied in Baltimore, Maryland. Allen J. Scott (1971) explains that transshipment networks are made of intermediate points (transshipment points) through which the "commodity" is passed on the way to the destination (23). The researchers found that this system, including transfer stations, would yield savings in the total annual cost (28).

Currently, LA procedures are applicable to numerous kinds of problems. Models, heuristic programs, and algorithms are still being developed to solve problems in artificial or abstract environments, so glitches in the procedure can be found. Allen J. Scott (1971) has stressed LA's importance as a tool for theoretical analysis (33). In addition, this procedure has been applied to numerous problems of the public sector, and the results obtained from such studies have had effects on policy mechanisms (Scott 1971, 33). However LA also has some limitations and drawbacks: it has been depicted as cumbersome and time consuming (Cooper 1963, 331; Kuehn and Hamburger 1963, 654; Densham and Rushton 1992, 295, 302; Lam and Liu 1996, 321; Hsieh and Tien 2004, 1019), it poses difficulties for reaching global optimal solutions (Scott 1971, 32; Densham and Rushton 1992, 290; Rushton 1988, 109), and presents data aggregation issues (Gosh and Rushton 1987, 8; Logan 1985, 144; Goodchild 1979). Other issues stressed by Allen J. Scott (1971) are that this model does not seek to describe a real system, as it represents an optimized ideal state to which real systems aspire (2). In addition the location-allocation systems are highly unstable spatially and temporally due to changes in the spatial structure of demand or supply points and to the progressive obsolescence of central facilities, among others (Scott, 1971, 101). As expected, these may alter the conditions under which the system may be optimal or near to optimal. Due to the limitations presented, it is important to keep in mind when using LA procedures that in some cases the results obtained may be completely unrealistic. Although true, the results could be used as part of more comprehensive research of which LA makes up only the first step. Once the flows and numbers are given by these methods, alterations to the results could be carried out based on, among others, (more realistic) demographic, political, cultural, or environmental parameters using GIS software.

As mentioned at the beginning of this section, LA procedures are spatial and geographic in nature. The origins of these methodologies trace back to scholars that carried out geographic research and that had a profound influence in this discipline. This is why it has been widely employed in numerous geographic studies. Most of the research mentioned was carried out by geographers, for instance, Ghosh and Rushton (1987), Logan (1985), Goodchild (1979), Goodchild and Massam (1969), Densham and Rushton (1992), Rushton (1988), Scott (1970 and 1971), Osleeb and Cromley (1978), Thomas et al. (1991), Current and Ratick (1995), and Morrill (1976).

The least-cost model developed in this research has relations with some of the environmental research already presented. This research is predominantly one of practical application, in which a model of least cost transport and allocation of waste is developed to try to alleviate the waste management crisis present in Puerto Rico. Even though geographers have used these methods to deal with waste management systems, no similar research has been carried out in this island. This research tries to discover if the current waste distribution across Puerto Rico is carried out in an efficient manner and how an ideal and optimal distribution of waste would look within five years when more than half of the present landfills will be closed. Any governmental decision made in relation to the relocation of landfills or any other waste management infrastructure could have repercussions in other areas of environmental geographic enquiry, due to the fact that it could awaken local opposition or could be questioned from the perspective of environmental justice.

CHAPTER THREE

METHODOLOGY

According to the Solid Waste Management Authority (ADS), one of the most imminent waste management issues that has to be dealt with on the island is the re-distribution of the allocation of solid waste (ADS 2001b, np; Maysonet 2002). This is due to the fact that within a year there will not be enough landfill space to provide for the amount of solid waste that is generated on the island, especially in highly populated areas such as the Metropolitan Zone of San Juan. In addition, there is already an inefficient and uneven distribution of waste management infrastructure throughout the island and this increases cost. Facilities are not equally spread across the regions of the island according to population needs and waste generation levels.

For this research, data is collected and then a least-cost model is developed for the operational landfills on the island. A second step repeats the process for the landfills that will be open within five years. The software packages of ArcView and ArcInfo are utilized for the model development analysis. After this phase of the research, the "near-to-optimal" distribution posed by the model is compared to the regional system that has been proposed by the ADS for the management of waste. In addition, other waste-related infrastructure is included in the analysis.

The data used in this research was obtained from governmental agencies of Puerto Rico, the factfinder census website, and the ESRI website. The Planning Board of Puerto Rico provided shape files of the municipios, landfills, centros de depósito comunitario ["drop-offs"], transfer stations, and roads, among many others. ADS provided many documents and tables related to the landfills' operation. The ESRI and the census websites supplied shape files and tables on the demographics of Puerto Rico.

First, tables and maps on the commonwealth's demographics are prepared for comparison with the waste generation indices. Then indices of waste generation, landfill capacity, and other infrastructure are presented, and their spatial and regional distributions assessed.

The analysis uses landfill capacity (supply capacity), waste generation by each municipio (demand capacity), and landfills' life expectancy. The ADS provided tables (ADS 2002) that contain information on landfill (supply) capacity. It is important to stress that several of these tables with the same data provided by this governmental agency present different information. This poses a problem of accuracy for the research. Rosa Quiles (2003), an employee of the agency, explained that in many instances the differences in data are due to the fact that one table substitutes for the other, even if they are a month apart because the landfill capacity is constantly changing. In the case of the generation of waste by each municipio, there are two tables available to use, the "Projected Population and Municipal Solid Wastes for the Year 2010 for Puerto Rico" (Quiñones, Diez, Silva and Associates and Brown and Caldwell 1995, TABLE 2-1) which was developed in the 1995 Plan (Quiñones, Diez, Silva and Associates and Brown and Caldwell 1995), and "Cantidades de desperdicios sólidos, estudio de 1994" (Quiñones, Diez, Silva and Associates and Brown and Caldwell 1995, TABLE A-1), calculated by a consulting firm (Eco Futures) for the Authority during 1993. The data provided in the latter table is the one used in this research because it seems more realistic than the projections carried out for 2010, when it is presumed that the island had already reduced waste by 35 percent through recycling (Appendix A). In the case of the life expectancy of each landfill, different tables present that information. For this research the life expectancy index used is from the “Plan estratégico para el manejo de los residuos sólidos en Puerto Rico” (ADS 2003, np) because it is the latest and most up-to-date data available. All the data regarding landfill’s operation, including life expectancy, is contained in Table 5.1, which will be presented in the results.

The ADS determines the landfill capacity by calculating an average weight for the waste delivered to each landfill during a week-long period. The dumping rate, which is the per capita generation of waste, is calculated by weighing and characterizing the amount of waste that arrives at each landfill during a week-long period. An average is obtained based on a 52-week year. This average is divided by the total population of the municipio that contains the landfill. A profile is developed for each one of the municipios that do not contain landfills, based on commercial, population, and industrial development characteristics. Based on this profile, a “conversion factor” is calculated in order to apply the average results of waste from the municipios that contain landfills to the municipios that do not (Quiles 2003). This data was obtained by the Authority from a characterization study carried out by the private firm Eco Futures (1993) (Quiñones, Diez, Silva and Associates and Brown and Caldwell 1995, TABLE A-1).

The life expectancy of each landfill is calculated by the ADS taking into consideration the following: the amount of solid waste that the landfill receives, the characteristics of the solid waste that is deposited in it, the methods used to bury the waste material, the type and quantity of the material used to cover the waste, the size of the landfill, the total impacted land area, and the employees and equipment available in each, among others (ADS 2001a, 2).

In this research the values of per capita waste generation were verified using the following equation:

$$\left(\frac{\text{Total Generation of each Municipio}}{\text{Total Population of each Municipio}} \right) \qquad \text{X } 2{,}000$$

This index is calculated by dividing the amount of solid waste generated by each municipio by its total population. If the value of waste produced by each municipio is provided in tons it can be converted into pounds by multiplying the result by 2,000.

Even though the values that will be calculated are a good way to verify the numbers provided by the governmental agencies, the values will not be completely realistic because the landfills receive additional waste from private companies that deliver waste from diverse municipios (which are not always the same and are not specified in the data) and governmental agencies.

Figure 5.1 (presented in Chapter 5) was created using the indexes previously mentioned (total landfill supply capacity, landfill's life expectancy, and total generation per each municipio). For this graph, the life expectancy of each landfill is used to determine the total available supply capacity after 2003 (the date that the life expectancy values were calculated). The total demand values used in the graph are the ones provided by the table "Cantidades de desperdicios sólidos, estudio de 1994" [Amounts of Solid Waste, 1994 Study] (Quiñones, Diez, Silva and Associates and Brown and Caldwell 1995, TABLE A-1) (used in the development of the least-cost model). In the graph this value of total demand is presented as static over time, even though this will not be the case in reality. This is due to the fact that the levels of waste recovery (or deviation) have not changed as expected, and it is not clear how they will change over the coming years. While the levels of waste deviation increased slowly, the levels of waste generation have presented trends of slow increase (Table 4.6), so it is not clear if the total waste that will reach the landfills per day will increase or decrease and in what proportions.

In the next step, the least-cost model is developed using principally the ArcInfo software. The island-municipios of Vieques and Culebra are excluded from the analysis. Under this model the landfills are the supply points and each county represented a consumer point with demand for a "commodity."

Before developing the least-cost model, the data is prepared. First, the shapefile with the landfills in operation at present is fixed. A total of twenty-seven landfills are included in the analysis (Table 3.1 and Figure 3.1). The next step of the analysis involves creating a shape file (in ArcView) of the landfills with a life expectancy greater than five years (Table 3.2 and Figure 3.2). A total of ten landfills (supply centers) will be available five years from now. The north (in particular the northeast) and the center of the island are the regions that ended up with the fewest landfills.

In the location-allocation analysis using ArcInfo, a table of the centers must be created which identifies the centers and some of their parameters. This table is created and contains the fields (or items) of: center_#, supply_ite, candidate, name, and roads2-id. It is created in Excel and exported into ArcInfo (Table 3.1).

Highways, primary roads, secondary roads, and tertiary roads constitute the road layer. Tertiary roads are included in the analysis because many waste-related facilities, including the landfills, are located on them. On the contrary, all the roads of the offshore

Table 3.1 Landfills Currently in Operation, Included in the Analysis (27) (2003)

Center#	Name	Roads4_ID	Supply (tons/day)	Candidate
1	Añasco	6621	150.0	2
2	Arecibo	1777	850.0	2
3	Arroyo	12949	105.0	2
4	Barranquitas	9768	65.0	2
5	Cabo Rojo	12599	140.0	2
6	Carolina	4812	900.0	2
7	Cayey	10610	250.0	2
8	Fajardo	7343	346.0	2
9	Florida	4993	30.0	2
11	Guayama	13303	77.0	2
10	Guaynabo	6385	300.0	2
12	Hormigueros	10846	40.0	2
13	Humacao	10749	2,300.0	2
14	Isabela	550	76.0	2
15	Jayuya	9521	58.0	2
16	Juana Díaz	12350	200.0	2
17	Juncos	8182	315.0	2
18	Lajas	12521	40.0	2
19	Mayagüez	8615	350.0	2
20	Moca	2947	600.0	2
21	Ponce	12745	1,200.0	2
22	Salinas	13613	417.0	2
23	Toa Alta	4959	328.0	2
24	Toa Baja	3061	2,500.0	2
25	Vega Baja	1629	800.0	2
26	Yabucoa	11505	105.0	2
27	Yauco	12766	425.0	2
Total			12,967.0	

(ADS 2002)

islands of Vieques and Culebra are eliminated. (Figure 3.3) In the allocation procedure carried out in ArcInfo “commodity” or service flows take place through this network system. As explained by Lupien, Moreland, and Dangermond (1987) the inclusion of network analysis in analysis using GIS software has the advantage of calculating realistic flow constraints, due to the fact that impedances are extracted from the database management system. The inclusion of a network system, in this case of roads, represents an advantage to the (least-cost) model that will be developed because more realistic

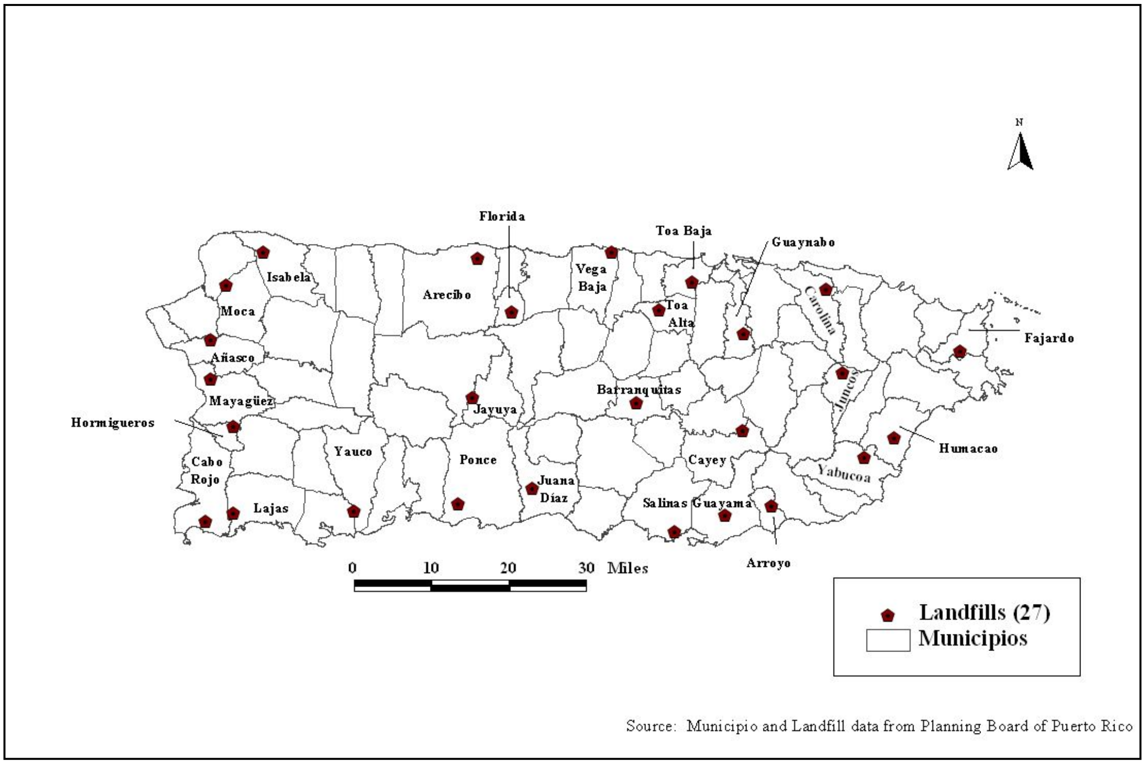


Figure 3.1 Landfills Currently in Operation, Included in the Analysis (27) (2003)

distances are used, as opposed to straight linear distances. Then a point theme that represents the centroid of each municipio is created using the ArcView script "Polygon Centroid to Point Event Theme." These centroids represent the municipios in the analysis and contain all of their attributes.

The shape files roads, centroids of municipios, and landfills are converted into coverages using the Arc Toolbox. Then the POINTNODE command is used to assign the attributes of the centroids to their closest node in the roads network. This is done a second time to add the attributes of the landfills to the roads network. Next the RENODE command is used on the roads coverage in order to set up the network and avoid the repetition of node IDs.

This entire procedure is carried out twice. Once for the landfills in operation at present and once for the landfills that will be open within five years. For analyses,

Table 3.2 Landfills that will be Open for 2008 (10)

Center #	Name	Roads10_ID	Supply (tons/day)	Candidate
1	Añasco	6621	150.0	2
2	Arecibo	1777	850.0	2
3	Cabo Rojo	12599	140.0	2
4	Fajardo	7343	346.0	2
5	Florida	4993	30.0	2
6	Humacao	10749	2,300.0	2
7	Mayagüez	8615	350.0	2
8	Ponce	12745	1,200.0	2
9	Salinas	13613	417.0	2
10	Yauco	12766	425.0	2
Total			6,208.0	

(ADS 2002)

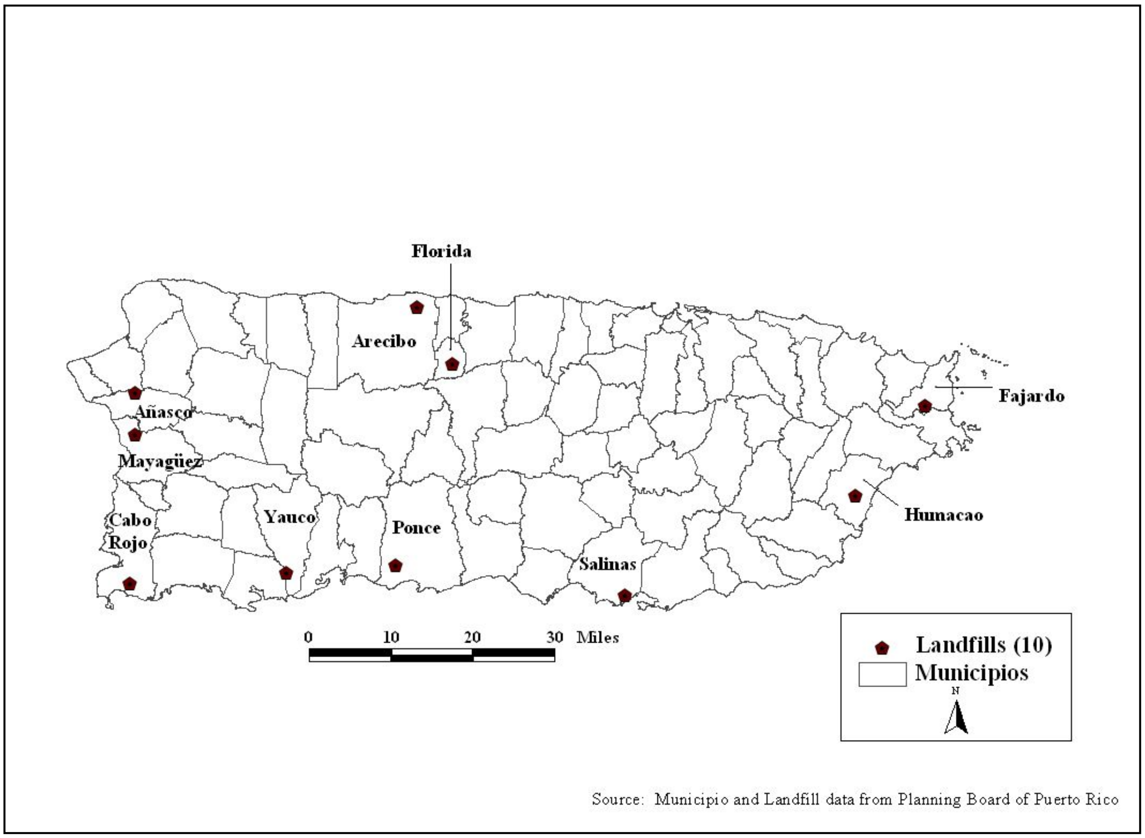


Figure 3.2 Landfills that will be Open for 2008 (10)

separate shapefiles and coverages of the road network and landfill are used. Then the least-cost model is developed. The ArcInfo software performs the analysis assigning each demand node to its closest facility and following a 0/1 integer assignment. This method of assignment presents some limitations to this research because, even now, some municipios in Puerto Rico send their waste to more than one landfill.

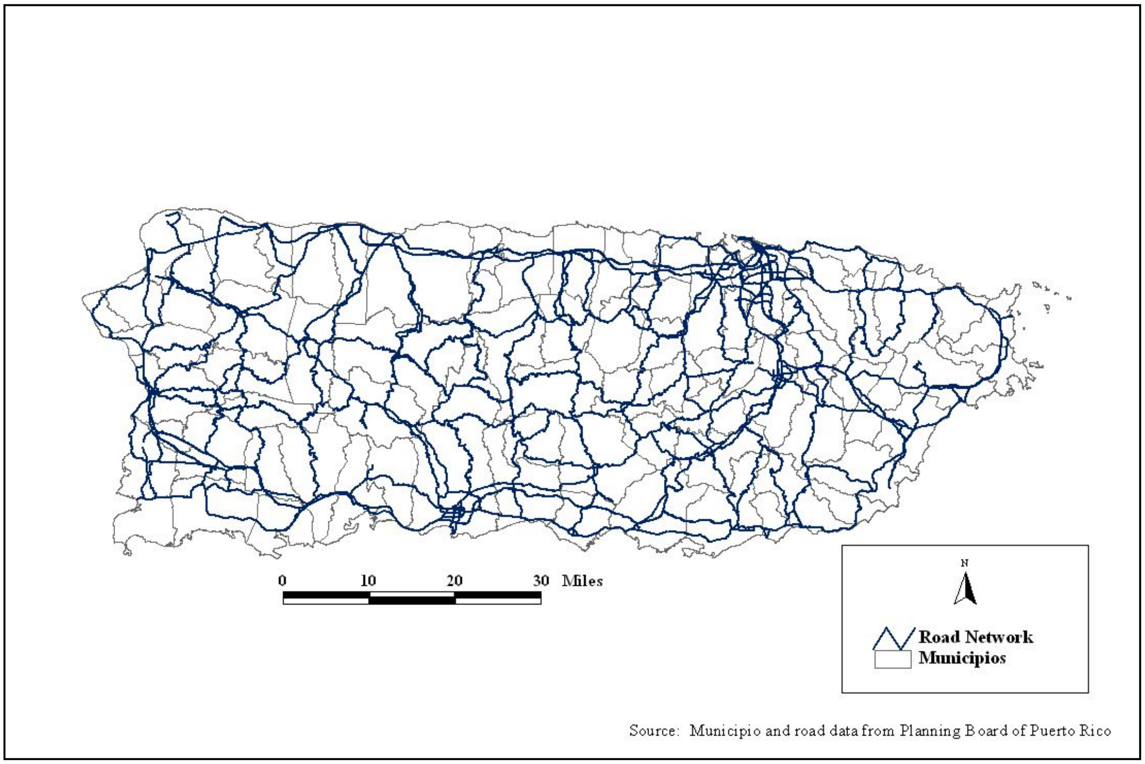


Figure 3.3 Road Network Used in the Methodology (2000)

First, the LOCATEALLOCATE command (in Arc Info) is used with MINDISTANCE model in order to find the minimum total and average distance travelled if the landfills would supply a service to their nearest neighbor (without taking supply capacity into consideration). This command can be carried out using one of six available models, which are designed to solve different types of problems (Environmental Systems Research Institute, Inc. 2001). The MINDISTANCE model is the p-median problem, which tries to minimize the total weighted distance between supply and demand points (Beaumont 26, 1987). This is carried out using the following coverages: roads, landfills in operation at present (and landfills in operation for 2008), and the centroids of the municipios.

Then the ALLOCATE command is used to develop the model using distance and capacity constraints. This command carries out allocation by assigning features to their closest center, based on the demand available, until the maximum impedance or resource capacity of the center is reached (Environmental Systems Research Institute, Inc. 2001). In this way supply service zones are established. This analysis is performed on the presently operating landfills in order to compare it with the present distribution of waste and determine how efficiently distributed it is today. In addition, it is performed in the landfills that will be open by 2008 to have an idea of the changes in the distribution of waste that will occur once nineteen of the landfills close.

The ALLOCATE command of ArcInfo uses a shortest-path algorithm, of which the most well known is Dijkstra's algorithm. The software calculates the cost-minimizing route by choosing the node with the shortest path from a candidate list. In each step, the nodes that present the shortest route are added to the solution table, which presents the final route. The final result is reached when no more nodes can be reached (Environmental Systems Research Institute, Inc. 2001).

An example of the command line used for location/allocation (using the LOCATEALLOCATE command) in ArcInfo is:

- netcover roads10 route
- demand # demand
- centers centers # # supply_ite
- locatecandidates centers candidate
- locatecriteria MINDISTANCE
- locateallocate outalloc outcenter outglob 10

To display the outputs of location/allocation the command line is:

- display 9999
- mape roads10
- spider roads10 node outalloc roads10# site1

An example of location-allocation using the command line for the ALLOCATE command is:

- netcover roads10 route
- demand # demand
- centers centers # # supply_ite
- allocate centers in unconstrained node node

To display the outputs of the ALLOCATE command:

- display 9999
- mape roads10
- routelines roads10 route #

Once the software provided the “ideal” scenarios, utilizing capacity and distance constraints, then the results are analyzed and compared with the present distribution of other operational (waste-related) infrastructure, e. g. MRF, compost centers, and transfer stations, and how service would be provided throughout the island within five years. In addition, the distributions proposed by the model are also compared with a proposed regional configuration (by the ADS).

CHAPTER FOUR

WASTE DISPOSAL AND MANAGEMENT IN PUERTO RICO

Puerto Rico has been experiencing a crisis in solid waste management since the middle of the twentieth century; but it was not until its last three decades that there has been an awakening in environmental awareness and pressure groups have begun to encourage the government to take action and solve this problem. About twenty-seven of the twenty-nine landfills that receive domestic waste on the island do not keep up with the local and federal environmental regulations. According to the Director of the U. S. Environmental Protection Agency, Carl Axel Soderberg, in 2002 only the landfills in Ponce and Humacao followed the established federal regulations (Fernández 2002, 52). Many refuse disposal facilities occupy sites that represent a serious threat to environmental resources and to human health. They exhibit deficiencies in numerous ways: constant spontaneous fires, improper daily cover, inadequate fencing, improper entrances and exits for trucks, the lack of leachate and gas monitoring instrumentation, and proximity to communities. For instance, the Añasco landfill is located adjacent to a community that must live with an unbearable smell and flies (Matías 2002, 47). Other examples are the Mayagüez landfill, which is close to El Maní and Cuba communities, and the Salinas landfill which is also contiguous to various communities (Sosa Pascual 2003, np).

Landfills that I visited in 2002 in the Municipios of Toa Baja, Toa Alta, and Arecibo did not follow federal regulations. None of the sites had the appropriate gas or leachate management systems. In addition, the garbage was covered incorrectly in many areas of the sites. At the date of my visit (2002), Toa Alta's landfill did not have a scale to weigh the trucks that delivered waste (Lasén 2002; Palacios 2002).

Some landfills are located over sinkholes that replenish important underground water sources, many are close to surface (and underground) bodies of water, and some are located near by or inside important forests or natural reserves. For example, the Arecibo landfill occupies a portion of the Natural Reserve of Caño Tiburones. It is an important wetland (in the north coast) with great biodiversity and an important niche for the reproduction of varied aquatic, terrestrial species, and migratory birds. The Yauco landfill takes up 29.1 acres inside the Dry Forest (southwest), another important Natural Reserve that has unique conditions for the preservation of faunal and floral species. This same landfill is also close to the Santa Rita and Del Valle de Barinas aquifers, which supply water to most of the population. In 2002 this landfill was expanding to 97 acres. On the other hand, the Mayagüez landfill is located adjacent to the Boquilla canyon, so when it rains the water takes the trash to the Grande de Añasco River, which supplies water to 98 percent of the population (Sosa Pascual 2003, np). The Toa Alta landfill is "located in the midst of a sinkhole that feeds into ground water supplies" (Lenart 1995, 12).

Environmental scientists have denounced that the landfills have received toxic or hazardous waste (Fernández Colón 1988, 16). This is only one part of the story because illegal dumpsites are spread all over the island. There are cases, such as in the Barrio Diego Hernández of Mayagüez, where the municipal government created an illegal dumpsite of scrap and tires. According to members of this community, municipal trucks bring garbage to a location that is adjacent to the children's baseball park (Rivera Vargas

2003, 50). In other examples, the municipalities of Quebradillas and Camuy created illegal dumpsites last year on public lands because they did not have the economic resources to deposit their garbage in a landfill. The Environmental Quality Board fined them for these actions (Reyes Faría 2002, 7; Rosario 2002, 62).

Another issue that has surrounded waste management in the island for decades is the question of a tariff for the collection of refuse by the population. This policy has received general opposition and it has never passed. As the last director of the ADS, Ricardo Rodríguez, expressed, this charge could be applied in different ways, such as establishing a fixed tariff (regardless of the amount of waste generated), another option could be a stamp system that could be adhered to the trash bags, or a charge according to the amount of waste generated in each household. Some experts consider that the latter methods would motivate reduction and material separation at the place of origin (ADS 2001b, np). However, as the Executive Director of the Federation of Mayors of Puerto Rico, Isabelo Molina, explained, a consensus has never been reached on this matter, especially on the amount of the tariff and the mechanism that will be used for charging it (La Semana 2002, 11).

The accelerated population growth experienced especially since the mid-twentieth century and the high levels of population density have aggravated the refuse problem. Today 3.8 million people populate the island, which makes a population density of 1,112 per square mile. In northeast Puerto Rico, the San Juan metropolitan zone extends over about eight municipios and keeps spreading. It constitutes the economic center of the island, followed in economic importance by the city of Ponce (south), and to a lesser extent due to economic problems during the last decades, by the city of Mayagüez (west).

The municipios with the largest population are linked to the three most important economic, industrial, and commercial clusters on the island (Table 4.1 and Figure 4.1). The municipios with the highest population densities, are mostly located in these economically important regions, but the top five are located at the Metropolitan Zone of San Juan (Table 4.2 and Figure 4.2) (Appendix B). The high levels of population concentration in this region are alarming since about 1.2 million people live there, and most of the landfills around this zone will be closed within the next year (U. S. Census Bureau 2000).

Table 4.1 Fifteen Municipios with the Highest Population (2000)

Municipio	Population	Density per square mile
San Juan	434,374	9,084.4
Bayamón	224,044	5,048.0
Ponce	186,475	1,625.5
Carolina	186,076	4,105.1
Caguas	140,502	2,394.6
Arecibo	100,131	794.8
Guaynabo	100,053	3,688.3
Mayagüez	98,434	1,267.9
Toa Baja	94,085	4,062.0
Trujillo Alto	75,728	3,650.0
Aguadilla	64,685	1,767.8
Toa Alta	63,929	2,336.0
Vega Baja	61,929	1,349.5
Humacao	59,035	1,318.6
Río Grande	52,362	862.3

(U.S. Census Bureau 2000)

In addition to the high population concentration, the Puerto Rican economy has shifted from agricultural to industrial since the 1950s. Today the Puerto Rican society is well known for being highly urbanized and for having high levels of consumerism, in

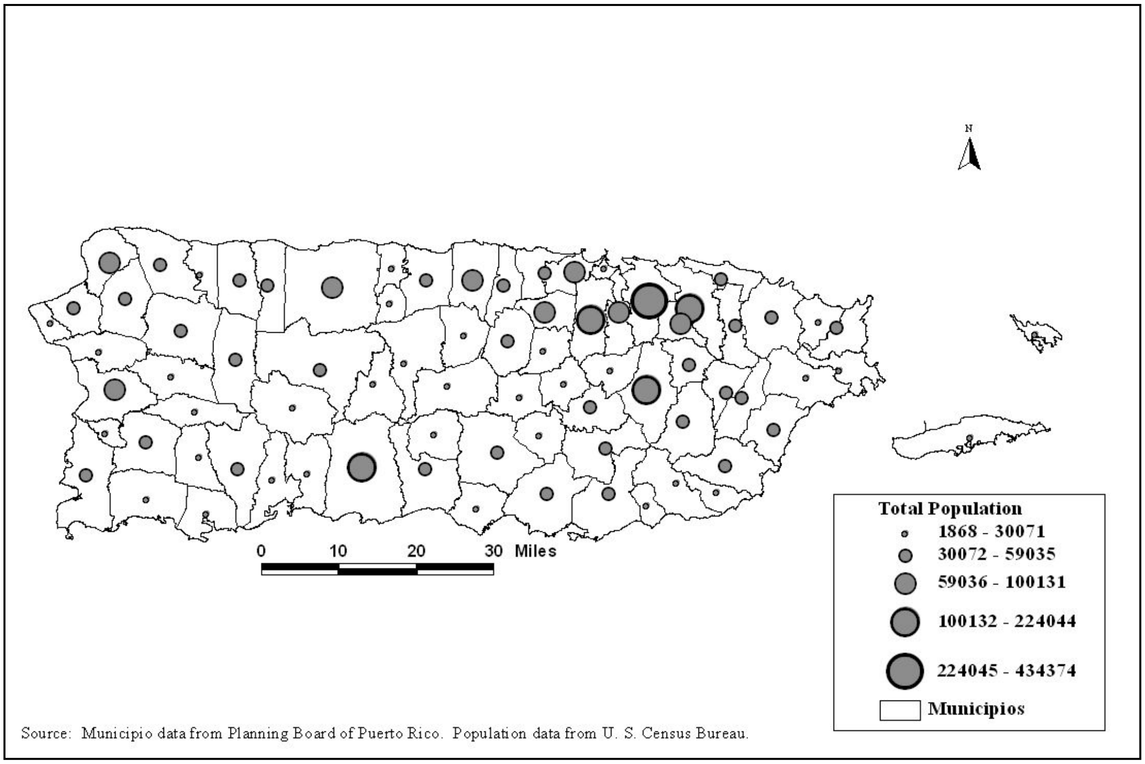


Figure 4.1 Municipios' Total Population (2000)

many instances of disposable (recyclable or not recyclable) items (ADS 2003, np). The consumption patterns are directly related to the market economy that exists and the increase in per capita income, among other factors (ADS 2003, np). In addition, products have a shorter life span than in previous decades forcing the consumer to replace them periodically. This has caused a steady increase of residues through out this and the last century. Another element that worsens the situation is that Puerto Rico is a small island with a few isolated places for the disposal of waste. As Christine McCoy explains, "the complex, unique, and finite nature of island ecosystems make them extremely susceptible to solid waste pollution" (McCoy 1996, 126). And last but not least, the crisis that this archipelago confronts today is in part due to the indifference that one political administration after another have had towards it (Carrasco 1986a, 15).

Table 4.2 Fifteen Municipios with the Highest Population Density (2000)

Municipio	Population	Density per square mile
San Juan	434,374	9,084.4
Cataño	30,071	6,232.5
Bayamón	224,044	5,048.0
Carolina	186,076	4,105.1
Toa Baja	94,085	4,062.0
Guaynabo	100,053	3,688.3
Trujillo Alto	75,728	3,650.0
Caguas	140,502	2,394.6
Toa Alta	63,929	2,336.0
Aguadilla	64,685	1,767.8
Loíza	32,537	1,673.4
Ponce	186,475	1,625.5
Hormigueros	16,614	1,467.1
Dorado	34,017	1,458.2
Juncos	36,452	1,371.1

(U.S. Census Bureau 2000)

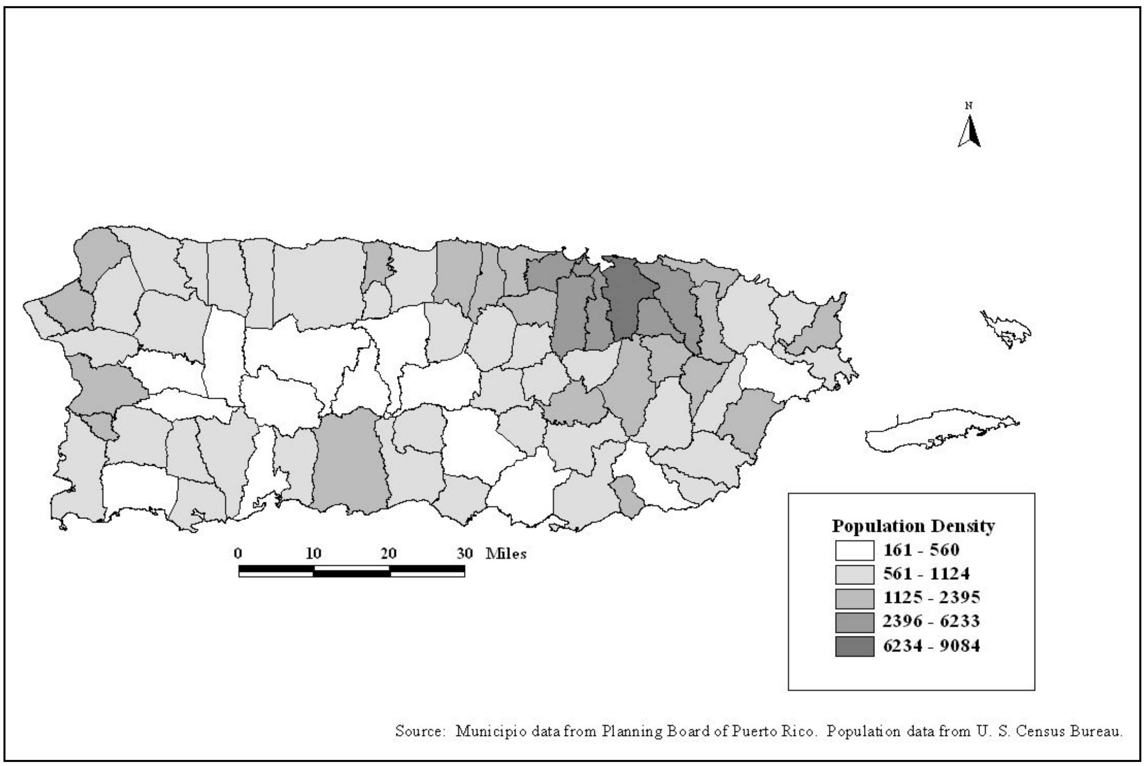


Figure 4.2 Puerto Rico's Population Density (population per square mile) (2000)

The per capita waste generation represents an average of waste production per individual in a society. Due to the high levels of population density, rapid population growth, and the high levels of consumerism one expects to find high levels of per capita generation of waste, and to see higher levels concentrated in specific regions (ADS 2003, np). As expected, the municipios that show the highest per capita solid waste generation are within the island's economic core: the Metropolitan Zone of San Juan (Cataño, Toa Baja, Carolina, and Guaynabo), the city of Ponce (Ponce and Guayanilla), and the city of Mayagüez (Mayagüez) (Table 4.3 and Figure 4.3). In contrast, many central and eastern municipios present low levels of per capita generation of Municipal Solid Waste (MSW). In particular municipios such as Trujillo Alto and Toa Alta have high levels of population density, but very low values of per capita generation of waste (Appendix A and B).

Table 4.3 Fifteen Municipios with the Highest Per Capita Waste Generation (1993)

Name	Generation (tons/day) (1993)	Per Capita Generation (lb/person/day) (1993)	Population (2000)
Cataño	521.5	34.7	30,071
Toa Baja	608.1	12.9	94,085
Barceloneta	96.8	8.7	22,322
Ponce	796.2	8.5	186,475
Juncos	150.3	8.2	36,452
Carolina	554.8	6.0	186,076
Guaynabo	297.8	6.0	100,053
Fajardo	117.4	5.8	40,712
Mayagüez	273.1	5.5	98,434
Guayanilla	60.7	5.3	23,072
Dorado	86.2	5.1	34,017
San Juan	1,041.5	4.8	434,374
Caguas	334.5	4.8	140,502
Santa Isabel	48.6	4.5	21,665
Luquillo	43.2	4.4	19,817

(Quiñones, Diez, Silva, and Associates and Brown and Caldwell 1995, Table A-1)

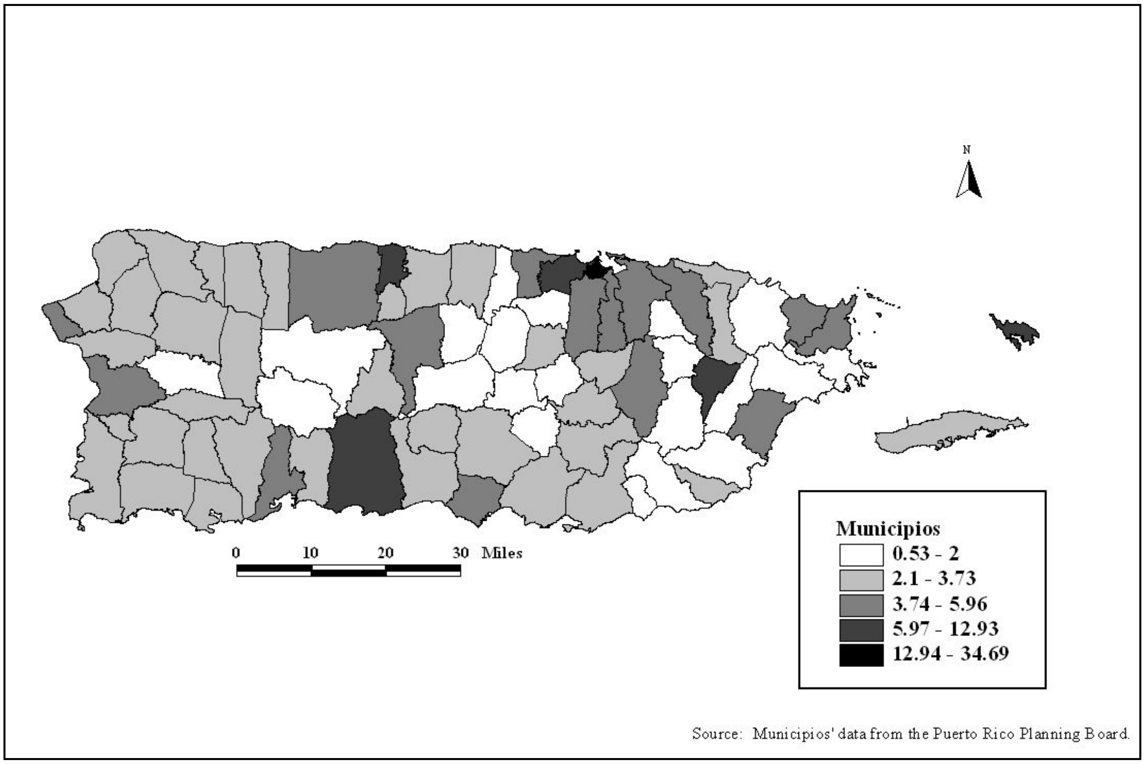


Figure 4.3 Per Capita Waste Generation (per Municipio) (lbs/person/day) (1993)

The total per capita waste generation for the island was calculated from the sum of all the municipios' waste generation (tons per day), divided by the total population of the island, and multiplied by 2,000. This equation yielded a total 4.24 pounds per person per day. According to the last study carried out by a consulting group for the ADS (Shaw EMCON/OWT, Inc. and Wehran – Puerto Rico, Inc. 2003, E-11), the total pounds per day per person is 3.91. The U. S. Environmental Protection Agency estimates the value to be, after recycling and composting, around 3.15 pounds/person/day (Shaw EMCON/OWT, Inc. and Wehran – Puerto Rico, Inc. 2003, E-11). Even though these values might seem high for an underdeveloped territory such as Puerto Rico, they are certainly not as high as expected due to the high levels of consumerism, population growth, and population density, that were already mentioned.

The per capita index is derived from the total demand per municipio, or the total number of tons generated by each municipio during a specific time period. When the total demand is evaluated geographically, the municipios with the highest production of MSW are also located in the economic centers of the island, but represent a high conglomeration in the San Juan Metropolitan Zone (Table 4.4 and Figure 4.4). The 2003 characterization study (Shaw EMCON/OWT, Inc. and Wehran – Puerto Rico, Inc. 2003, Table E-3) reveals very similar results, even though the unit of measurement differs in the time scale; they measured the tonnage per week, while this research considers days (Table 4.5). The values of total tonnage generation for the municipio of Cataño are exceptionally high for its small territory. The characterization study (E-11) explains that it is due to the presence of two private transfer stations within its boundaries that receive waste from various municipios, including San Juan. In 2003 a total 3.6 million tons of solid waste were generated (Shaw EMCON/OWT, Inc. and Wehran – Puerto Rico, Inc. 2003, E-11). Ranked by volume, the leading waste types are: yard waste (20.4 percent), paper/cardboard (19.3 percent), construction debris (17.1 percent), organic waste (12.9 percent), plastic (10.5 percent), metals (10.5 percent), and glass (2.4 percent) (Table 4.6) (Shaw EMCON/OWT, Inc. and Wehran – Puerto Rico, Inc. 2003, E-11). The total number of tons of solid waste generated in the island have been increasing. However, the total garbage generation has been starting to grow at a slower rate (Table 4.7).

According to the last characterization study carried out on the island (Shaw EMCON/OWT, Inc. and Wehran – Puerto Rico, Inc. 2003, E-11) the ten landfills that receive the largest volume of waste (per week) account for nearly 75 percent of the total waste generated (Table 5.2). About half of those landfills are located in the east and

Table 4.4 Fifteen Municipios with Highest Values of Waste Generation (1993)

Name	Generation (tons/day) (1993)	Per Capita Generation (lb/person/day) (1993)	Population (2000)
San Juan	1,041.5	4.8	434,374
Ponce	796.2	8.5	186,475
Toa Baja	608.1	12.9	94,085
Carolina	554.8	6.0	186,076
Cataño	521.5	34.7	30,071
Bayamón	467.3	4.2	224,044
Caguas	334.5	4.8	140,502
Guaynabo	297.8	6.0	100,053
Mayagüez	273.1	5.5	98,434
Arecibo	209.0	4.2	100,131
Juncos	150.3	8.2	36,452
Humacao	126.5	4.3	59,035
Fajardo	117.4	5.8	40,712
Barceloneta	96.8	8.7	22,322
Aguadilla	91.3	2.8	64,685

(Quiñones, Diez, Silva, and Associates and Brown and Caldwell 1995, Table A-1)

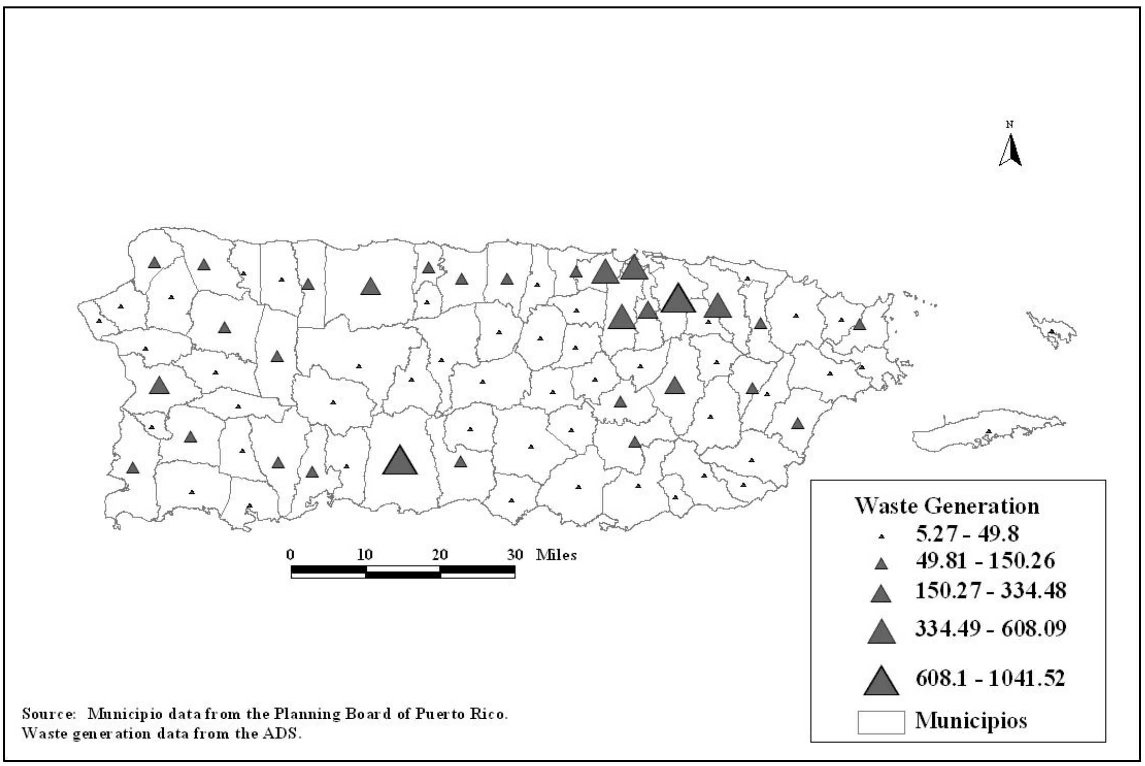


Figure 4.4 Waste Generation, Puerto Rico (tons/day) (1993)

northeast region of the island, while the rest are spread across the rest of the territory. As expected, the landfills that provide the service for the largest population coincide, for the most part, with the landfills that receive the most waste (Table 4.8 and 5.1).

Table 4.5 Puerto Rico's Generation Values (According to 2003 Characterization Study)

Municipio	Generation (tons/week)	% of Total
San Juan	8,148	11.8
Cataño	5,078	7.3
Ponce	4,762	6.9
Carolina	3,206	4.6
Caguas	3,104	4.5
Bayamón	2,894	4.2
Arecibo	2,056	3.0
Mayagüez	1,980	2.9
Toa Baja	1,855	2.7
Guaynabo	1,748	2.5
Humacao	1,421	2.1
Guayama	1,406	2.0
Aguadilla	1,296	1.9
Canóvanas	1,248	1.8
Juncos	1,226	1.8

(Shaw EMCON/OWT, Inc. and Wehran – Puerto Rico, Inc. 2003, Table E-3)

Table 4.6 Waste Characterization (According to 2003 Characterization Study)

Type of Material	Combined Percentage (weight)
Plastic	10.5
Paper/Cardboard	19.3
Metals	10.5
Yard	20.4
Organic	12.9
Construction/Debris	17.1
Glass	2.4
Household Hazardous Waste	0.5
Other	6.3

(Shaw EMCON/OWT, Inc. and Wehran – Puerto Rico, Inc. 2003, Table E-12)

Before the 1970s the solid waste in Puerto Rico was deposited in dumpsites and burned. These facilities were under the jurisdiction of the Department of Mines, which was a division of the Department of Natural Resources (today the Department of Natural and Environmental Resources). Over the years municipios stopped burning at dumpsites, but still there was no formal enforcement of existing garbage disposal regulations. Waste was also dumped in open or “unproductive” lands such as wetlands and sinkholes. After the 1970s dumpsite administration changed to the Health Department. However, each municipio was responsible of the management of waste material generated within its jurisdiction.

During the 1970s the government of Puerto Rico and the general population began to notice the devastating consequences that the improper disposal of waste had on the environment and human health. This recognition was reinforced by federal legislation that was being put into effect on the island. The Clean Air Act (1970), the Clean Water Act (1972), and the Resource Conservation and Recovery Act (RCRA) (1976) were among the regulations that established stricter controls over waste disposal methods (ADS 2003, np). In order to facilitate the new requirements the federal government assigned funds to the government of Puerto Rico. Despite this new legislation, all of the municipios tended to have poorly supervised or unregulated dumpsites in their territories.

Puerto Rican officials used part of the federal aid sent to the island to create the ADS in 1978. This is the governmental entity in charge of developing and implementing the infrastructure for the solid waste management in Puerto Rico. Among its functions is to plan for the entire Commonwealth of Puerto Rico, the management, recovery, processing, and final disposition of solid waste (ADS 2003, np). Originally, the Authority (ADS) was under the power of a government board and its director, but since

Table 4.7 Puerto Rico's Waste Generation (and Characterization) (1993 – 2001)

MATERIALS (tons/yr)	**1993**	**%**	**1994**	**%**	**1995**	**%**	**1996**	**%**	**1997**
Solid Waste	2,138,646.0		2,118,134.0		2,159,811.0		2,176,097.0		2,192,888.0
Plastic	4,092.0	1.6	3,001.0	1.1	3,459.0	1.2	4,546.0	1.6	4,363.0
Paper	22,219.0	8.8	30,783.0	11.3	31,421.0	10.5	31,855.0	10.9	30,979.0
Aluminum	17,921.0	7.1	25,708.0	9.4	32,813.0	10.9	24,555.0	8.4	30,488.0
Other Metals	90,980.0	36.2	96,080.0	35.1	96,878.0	32.3	115,300.0	39.5	110,281.0
Glass	12,000.0	4.8	9,332.0	3.4	7,378.0	2.5	6,373.0	2.2	6,417.0
Cardboard	104,351.0	41.5	108,471.0	39.7	128,401.0	42.8	102,071.0	34.9	100,761.0
Sludge/Garden Residues	0.0	0.0	0.0	0.0	0.0	0.0	116.0	0.0	785.0
Tires	0.0	0.0	0.0	0.0	0.0	0.0	7,322.0	2.5	23,745.0
Total	251,563.0	100.0	273,375.0	100.0	300,350.0	100.0	292,138.0	100.0	307,819.0
MATERIALS (tons/yr)	**%**	**1998**	**%**	**1999**	**%**	**2000**	**%**	**2001**	**%**
Solid Waste		2,210,190.0		2,233,130.0		2,228,037.0		2,233,130.0	
Plastic	1.4	4,186.0	1.6	5,473.0	1.8	5,870.0	1.9	15,234.0	6.6
Paper	10.1	37,826.0	14.2	41,569.0	14.0	41,981.0	13.9	31,088.0	13.5
Aluminum	9.9	25,522.0	9.6	30,943.0	10.4	33,938.0	11.2	32,806.0	14.3
Other Metals	35.8	67,509.0	25.4	83,422.0	28.1	101,252.0	33.4	65,318.0	28.4
Glass	2.1	5,140.0	1.9	3,313.0	1.1	3,799.0	1.3	3,886.0	1.7
Cardboard	32.7	92,433.0	34.8	86,679.0	29.2	83,670.0	27.6	56,115.0	24.4
Sludge/Garden Residues	0.3	3,024.0	1.1	10,979.0	3.7	16,528.0	5.5	14,139.0	6.2
Tires	7.7	30,083.0	11.3	34,291.0	11.6	15,729.0	5.2	11,128.0	4.8
Total	100.0	265,723.0	100.0	296,669.0	100.0	302,767.0	100.0	229,714.0	100.0

(ADS 2003, np)

1993 the Department of Natural and Environmental Resources hosted the agency. These changes eliminated the government board, but not of the director. Even though the Authority has kept its operational, judicial, and administrative autonomy, since 1993 it is under the supervision, evaluation, and auditing of the Secretary of the Department of Natural and Environmental Resources (ADS 2003, np).

Table 4.8 Landfills that Receive the Highest Amount of Waste (tons/week) (2003)

Name	Waste Received (tons/week)	Percentage of Tonnage Received
Humacao	12,951.0	18.7
Toa Baja	9,496.0	13.7
Ponce	8,500.0	12.3
Arecibo	3,791.0	5.5
Juncos	3,753.0	5.4
Yauco	3,136.0	4.5
Salinas	2,906.0	4.2
Aguadilla	2,697.0	3.9
Carolina	2,255.0	3.3
Fajardo	2,167.0	3.1

(Shaw EMCON/OWT, Inc. and Wehran – Puerto Rico, Inc. 2003, E-4)

The Solid Waste Management Authority (ADS) works in coordination with other governmental agencies that have jurisdiction over different aspects of the waste management process. One of these is the Environmental Quality Board (Junta de Calidad Ambiental), created in 1970. It is the agency in charge of developing environmental policy on the island. It is also in charge of enforcing the existing environmental laws. The Health Department (Departamento de Salud) intervenes, as supervisor for the Environmental Quality Board, in cases were citizens claim health problems as a result of the location of operational or closed landfills (or dumpsites). The Authority of Aqueducts and Sewage (Autoridad de Acueductos y Alcantarillados de Puerto Rico) is in charge of the collection, transportation, and disposition of the sludge from the water filtering and treatment plants. Another governmental entity is the Administration of Regulations and Permits (Administración de Reglamentos y Permisos), which among its functions is in charge of authorizing permits for land use or for the infrastructure construction on the island. The Planning Board (Junta de Planificación) is in charge, among other things, to establish the edification codes for land use. In this way it regulates the location of infrastructure for waste disposition. The municipios have always been in charge of the collection, transportation, and disposition of the solid waste generated within their jurisdictions. In addition, many operate landfills within their jurisdiction, independently or in conjunction with other municipalities. Some municipios have the personnel and equipment to carry out this task, others have contracted private companies to complete all or some of these tasks. For most of them the management of waste represents a problem because the collection, transportation, and disposition costs are economically prohibitive (Penchi 2002, 11). Some industries operate transportation, processing, and disposal systems to deal with their own waste; others use private collectors and deposit their waste in the only industrial landfill in the island, located in the municipio of Peñuelas (Quiñones, Diez, Silva, and Associates and Brown and Caldwell 1995, 2-2, - 2-3).

In 1994 there were sixty-four dumpsites around the island. In 1994, amendments to the Environmental Protection Agency's RCRA went into effect on the island and thirty-two dumpsites had to close. The rest of the dumpsites received a grace period of five to seven years to meet with the standards of the newly established regulations. One of the federal expectations was that the government would develop new facilities for waste processing such as transfer stations, compost centers, and recycling plants.

Landfilling has remained the preferred garbage disposal method on the island because it is the most economical in the short term. Therefore, many businesses involved in waste management support this method as an easy and profitable enterprise. However, the increasing restrictions and regulations posed by the federal and local governments on the design, construction, operation, and post-closure care (which according to the Subtitle D of RCRA is for 30 years) of landfills have raised the costs of this disposal method. Hans Tammemagi argues that, in the long term landfills are a much less economical option due to the following reasons: (1) they are permanent facilities that will have to be monitored and maintained for centuries after they close; and (2) they represent a huge potential threat to the environment (because they can cause a permanent loss of land resource, an impairment of groundwater, or degrade the atmosphere by gas emissions) (Tammemagi 1999, 38).

Due to those potential problems the Authority has to implement and promote waste processing and disposal methods that are environmentally and economically viable. This is something that has been put into practice in other parts of the world. An "integrated waste management" strategy refers to the use of a variety of technologies, such as reduction, reuse, recycling, composting, incineration, waste to energy, and landfilling, while the impact on the environment is kept to a minimum (Tammemagi 1999, 33; McCoy 1996, 1). The adoption of such an approach is costly, something that is an uphill struggle for a developing U.S. territory such as Puerto Rico. In addition to "integrated waste management," the government of Puerto Rico can approach waste-related management using the "community-based approach," presented by Christine McCoy (1996). This strategy, which has been used to deal with solid waste management, empowers citizens to take responsibility for decision making and changing local conditions (McCoy 1996, 126).

Many other methods of waste reduction, processing, and disposal have been proposed and evaluated by governmental entities on the island, but have been put into effect to a limited degree. Among such methods are incineration and recycling. There have been various proposals (from municipios and the central government) for the construction and operation of energy recovery plants for San Juan, Caguas, Cataño, and Guaynabo (among others) that have failed because of public opposition. These plants produce energy by reducing the solid waste up to 85 to 95 percent (ADS 1996, 5). Besides energy, other products of this process such as carbon dioxide, warm gases, dioxins, nitrogen compounds, arsenic, cadmium, and ashes have made this alternative controversial because of its potential for degrading the environment. However, according to Hans Tammemagi technological advances in emission control devices enable the removal of 90 to 99 percent of some of these pollutants (Tammemagi 1999, 153). He explains:

> the U.S. Clean Air Act of 1990 gives credit to utilities for reducing pollution by buying power from waste-to-energy incinerators. . . The U.S. Department of Energy estimates that waste-to-energy technology will be one of the four largest contributors to the nation's planned carbon dioxide reductions for the year 2000 (15 percent of it). (Tammemagi 1999, 158)

On the other hand, many argue that in order to reduce the levels of hazardous and dangerous gases and compounds released by incinerators, very sophisticated instrumentation has to be used, which makes this alternative prohibitive to an underdeveloped nation such as Puerto Rico.

Up to 1990 there were from 600 to 800 small incinerators in housing and business buildings all over the island, which processed from 2 to 50 tons of waste per day. Operators closed these incinerators when federal regulations went into effect. Incinerators had a bigger set back in the island in 2001 when the Puerto Rican Senate passed a joint resolution (Resolución Conjunta del Senado 9, February 5, 2001) that rejected incineration as an approved solid waste disposal technology in the Commonwealth of Puerto Rico (ADS 2003, np). A second resolution (Resolución Conjunta del Senado 733, December 28, 2001) forbids the ADS to invest public funds in the research, development, and construction technologies that use incineration (ADS 2003, np).

Recycling began to be promoted as a strategy approved by the government during the mid-1980s. Additional legislation, passed in the 1990s encouraged recycling. The Law 70 of September 18, 1992 entitled "Ley para la Reducción y el Reciclaje de Desperdicios Sólidos en Puerto Rico" [Law for the Reduction and Recycling of Solid Waste in Puerto Rico], established as public policy the development and implantation of strategies and programs to decrease the volume of solid waste that would end up in the landfills. This law established a hierarchy of methods for solid waste management, which are: reduction of the quantity of the solid waste generated; reuse of material; recycling and compost of material that can not be reused; recovery of energy as a resource as long as it conserves the quality of the air, water, soils, and other resources; and disposition of the material in landfills that does not meet federal and local regulations, and that can not be reused, recycled, or used for energy recovery (ADS 2003, np). The legislation assigned specific functions to the Authority in order to carry out these provisions, such as infrastructure development for the collection, processing, and marketing of recyclable material. This agency became the provider of technical assistance and orientation to municipios and public agencies; and it was supposed to establish the tariffs to be paid for the transportation, processing, and collection of recyclable solid waste, among others (ADS 2003, np). This law also established functions and requirements for public agencies, municipios, and private business (or industries). In addition, economic incentives were put into effect, such as differential charges for the collection of recyclable material, tax exemptions, and financing for the construction of recycling plants and for equipment acquisition (ADS 2003, np). The law stipulated a goal to reduce the volume of garbage disposed in landfills by 35 percent for the year 1995. Since the island has only reached 16 percent, the government has posed 2006 as the new target date (ADS 2003, np).

In 1996 the Puerto Rico legislature revised this law in order to incorporate new guidelines for the development of recycling programs. From that point on it was compulsory for each municipio to approve ordinances that established a plan explaining how recycling was going to be carried out within its territory. The Authority must approve local ordinances (ADS 2003, np). The Law 411 is an amendment of the Law for the Reduction and Recycling (1992), which makes recycling obligatory for any industry, factory, business, education institution, and tourist business that employ more than ten persons (full or part time). This amendment also established an itinerary for how waste would be reduced over the years in order to reach 35 percent for 2006 (ADS 2003, np). There also have been a series of executive orders related to this topic, such as “Orden Ejecutiva 1990” [Executive Order 1990] and “Orden Ejecutiva 2001” [Executive Order

2001] that encouraged recycling on the island. The Law 61 (2002) “Ley de Recuperación de Material Reciclable en los Complejos de Vivienda” [Law for the Recovery of Recyclable Material in Housing Complexes] obliges any (public or private) housing construction project after July 2003 to designate an area for the collection of recyclable material.

Most of the local regulations that encourage and promote recycling in the island are carried out through varied methodologies. Examples include drop-offs, material recovery facilities (MRFs), compost centers, and transfer stations. Some municipios have “centros de depósito comunitario” [drop-offs], established by the Authority, where individuals can take their materials every second or fourth Saturday of each month. The Authority’s and government’s goal is that each municipio will have a permanent drop-off in order to ease and promote recycling for a greater portion of the population.

Another option is the “bolsas azules” [blue bags], which are picked up in front of households. Blue bag collection is available in only some areas of the island because it is a community initivative. Material collected in the “centros de depósito comunitario” and through the “bolsas azules” systems go to “facilidades de recuperación de material” [material recovery facilities] (MRFs), in which the recyclable material is separated, compacted, and prepared to be sent to factories that convert it into new materials. The government granted subsides and financial aid to private enterprises to create these plants in 1993. Today only three of these structures survive - in Carolina, Humacao, and Hatillo. Many of the individuals and private business who were granted this aid did not go further with their plans of establishing these structures for economical and unknown reasons (Rivera Lasén 2002).

There are “clean” and “dirty” MRF facilities. The clean MRF receives recyclable material that has been segregated. The dirty MRF receives domestic solid waste to be segregated and potentially toxic waste, such as batteries and pneumatic tires, among others. Currently, the government has two clean MRFs operating in Humacao and Hatillo, and one dirty MRF in Carolina. The “facilidades de separación de desperdicios voluminosos” [facilities for the separation of voluminous waste] receive waste of larger size and take it to a final disposition. Then, rejected material is sent to the landfills, while the recyclable material is processed and prepared to be sold to recycling factories (in and outside of Puerto Rico) (ADS 2003, np).

The “centros de acopio” [recycling plants] buy segregated recyclable material from the “drop-offs,” MRFs, or municipios to process it partially. The material that they process is sold to other installations. All of these centers are privately owned.

The waste that reaches the landfills can also be reduced by means of compost production. This process consists of the termophilical (in presence of heat) and aerobic (in presence of O_2) decomposition of organic material (ADS 1996, 10). The material produced from this process can be used to cover the waste in the landfills, for erosion control, for gardening, or for the conditioning of soils, among others. There are different methods of composting, but three examples that have been proposed for the island are windrow, aerated static piles, and in-vessel system. The only operational compost plant of the island, which is located in Arecibo, uses aerated static piles to process the material. It processes around 50 tons of waste each day, and it is administered by Caribbean Composting, a private enterprise. The compost center that was constructed in the municipio of Toa Baja has not been put in operation because the communities that surround the project did not want it near by their homes and sued to halt operation (Lasén 2002; Avilés 2002).

Transfer stations are structures located midway between the landfill and the municipio. In these facilities crews transfer the garbage to larger trucks designed to travel longer distances and through rugged surfaces. These installations reduce transportation costs and preserve human resources (Quiles 2003). In addition, at these places toxic and recyclable material are separated from the garbage before its final disposal. There are transfer stations and mini-transfer stations on the island. The transfer stations receive collection trucks coming from the municipios and the trucks coming from the mini-transfer stations, where applicable. Workers in these structures separate recyclable and vegetative material. Small municipios or regions that do not generate great quantities of garbage have mini-transfer stations. The mini-transfer stations have big containers that temporarily store garbage until larger trucks transfer it to landfills or larger transfer stations. The material recovered in these structures is later sent to recycling plants for processing into new products or it is sold outside of Puerto Rico. There are two operational transfer stations and seven operational mini-transfer stations in Puerto Rico (ADS 2003, np). In addition, there are many privately owned stations around the island that were not included in this study.

Over the years different plans for the distribution of waste, landfills, and other related infrastructure have been advocated by the ADS and related government agencies. None of these plans have been put into effect completely due to frequent changes of political administration. The first of these “plans” was the “Plan Integral para la Recuperación de Recursos” [Integral Plan for the Recovery of Resources] of 1980, updated in 1982 and 1986, that proposed the establishment of seven regions, that would each contain an energy recovery plant (in the counties of San Juan, Carolina, Mayagüez, Arecibo, Humacao, Caguas, and Ponce). In addition, it also recommended the establishment of transfer stations in order to increase the recovery of material from the municipios. The recommendations of this plan were hardly put into effect. In 1991 the "Plan Regional de Ubicación de Facilidades" [Regional Plan for the Location of Facilities] was proposed. It recommended the establishment of twenty regions, which consisted of three plants of energy recovery (in the counties of San Juan, Guaynabo, and Arecibo), eleven regional landfills in the main island, six municipal landfills (which supply to one county only), three landfills of ashes and products of the energy recovery plants, and twenty transfer stations. This plan was not put implemented either, due to the lack of economies of scale, the high cost of implementation, and the lack of governmental support, among other reasons (ADS 2003, np). In 1995 the "Plan Regional de Infraestructura para el Reciclaje y Disposición de los Desperdicios Sólidos de Puerto Rico" became the government's public policy. It proposed a total of nine regions on the main island, and each one on Vieques and Culebra. It consisted of a total of two energy recovery plants (in the counties of Guaynabo and Arecibo) with their corresponding landfills of ashes and refuse; seven regions in the main island containing a landfill, and one region in Vieques and another region in Culebra each containing landfills, twenty-five transfer stations, five wood grinding plants, seven compost plants, seven facilities of recovery of clean material, seven facilities for recovery of dirty material, and nine facilities for separation of voluminous material. Since 2000 a new political administration came to power and repealed the "1995 Plan" as the public policy. Once again, a new Plan is under construction in order to solve the problems of the all the waste issues of the island, at least until another change in political power occurs.

There are local regulations that exert control or provide guidelines for waste management in Puerto Rico. Among these are the “Reglamento de Desperdicios Sólidos No Peligrosos” [Regulations for Non Hazardous Waste], which was promulgated through the resolution R-97-3-93. This statute regulates everything concerned with management, administration, operation, and transportation of non-hazardous waste (ADS 2003, np). Other related legislation includes the Law 171, as amended, “Ley de Manejo de Neumáticos” [Law for the Management of Pneumatic Tires], from August 31, 1996 and the Law 172, as amended, “Ley de Manejo Adecuado del Aceite Usado en Puerto Rico” [Law for the Adequate Management of Used Oil in Puerto Rico]. These two laws establish the system of tariff, collection, management, and disposition of tires and used oil, respectively. In addition, they establish for the proper use of these materials. A positive result of these two laws is that they establish a charge for managing and disposing oil and tire waste, which makes their collection, transportation, processing, and reuse economically viable (ADS 2003, np).

In 2000 the legislature passed Law 310: “Ley para la Prevención de la Contaminación” [Law for the Prevention of Contamination]. It states that any contaminant coming from any industry should be reused or recycled through the use of technology approved by the Environmental Quality Board and in accord with the applicable laws and regulations (ADS 2003, np). The new political administration, which has been in power since the year 2000, released an Executive Order in 2001 which stated as the waste management policy the priorities established by the Law 70 (Law for the

Reduction and Recycling of Solid Waste in Puerto Rico, 1992). It advocates reduction as the first priority and disposal in landfills as the last option that should be considered. These options are prioritized this way because the public considers that incineration and landfill disposal pose a high threat to the environment and the population. According to environmentalists, this has not been the case because the government plans to expand many of the present landfills in order to increase their life expectancy, and (as been admitted by the agency) to avoid impacting new areas (Sosa Pascual 2003, np; ADS 2003, np). More over, “Informe de estrategias para el manejo de los residous sólidos en Puerto Rico – vertedero y composta” [Report of the Strategies for the Management of the Solid Waste in Puerto Rico – Dumpsites and Compost] reveals that the ADS is considering the creation of a new landfill in the southern and central regions of the island (ADS 2001b, np; ADS 2001a, 7). In addition, there are plans to expand the landfill located in Florida to increase its total capacity to 120 tons per day, so other municipios such as Barceloneta and Ciales can use it. In 2002 the landfills in Ponce, Yauco, and Salinas were seeking the permits to expand, and in that way increase their life expectancy up to twenty years. The Ponce landfill was also trying to obtain the proper permits to open an area for industrial waste (Fernández 2002, 57). This is alarming as the Yauco landfill is located inside a natural reserve and close to important water resources, and Salina’s landfill is contiguous to various communities. Internal documents of the Authority explain that the expansion of the landfills in the municipios of Carolina, Cayey, Guaynabo, Juana Díaz, Guayama, Juncos, Cabo Rojo, Peñuelas, Humacao, and Fajardo has also been considered (ADS 2001a, 6; ADS 2001b, np). A total of fourteen landfills are making expansion plans.

There are other statutes of the Commonwealth of Puerto Rico that exert controls on the management of solid waste. Some of these statutes that should be mentioned are: “Ley de Incentivos Contributivos de Puerto Rico” (1987) (Law of Tax Incentives of Puerto Rico), which allows tax exemptions to recycling industries, businesses that buy more than 15 percent of their productions from recyclable material, and a 50 percent tax credit for infrastructure investments for the disposition of waste; “Ley Orgánica del Departamento de Recursos Naturales y Ambientales” (1972) [Organic Law of the Department of Natural and Environmental Resources], as amended, creates the governmental agency and gives to it the responsibility for planning, managing, helping conserving, and developing the natural resources of the island; and “Ley para Regir la Extracción y Excavación de Materiales de la Corteza Terrestre” (1976) [Law to Rule the Extraction and Excavation of Material from the Earth Crust] influences the activities carried out in landfill development and waste disposal (ADS 2003, np).

A good example of the federal legislation that controls waste management in the island is RCRA, which controls and regulates everything related to solid waste from its point of origin until its final disposal (ADS 2003, np). This law defines hazardous and non-hazardous material and regulates the type of material that can be deposited in landfills (ADS 2003, np).

Subtitle D of the RCRA regulates nonhazardous waste. It establishes controls over storage, transportation, processing, and disposition of solid waste. It specifies the criteria that operators should follow for the location, design, construction, and operation of landfills. For example, it mandates exclusion areas where the establishment of a landfill would pose a threat to the environment or human beings; e. g. areas prone to flooding within 100 years, reserves and forests, lakes and mangrove forests, urban areas, karst zones, habitats of species in danger of extinction, buffer zones around airports, and cultural and historical sites. It also specifies the care that should be taken after an installation's closure (Quiñones, Diez, Silva, and Associates and Brown and Caldwell 1995, 3-7). RCRA stipulates that landfills should be designed in a way to minimize the production and migration of leachates, to control the entrance and exit of superficial water, and to manage gases produced during the decomposition of the solid waste (ADS 1996, 15). Few Puerto Rican facilities follow these requirements. Leachate is the water that is or has been in contact with solid waste. It can get to the landfill with the waste or through horizontal (e. g. streams) or vertical (e. g. rain) movement. The "waste juices," as leachate is also called, are a dangerous source of contamination that threaten streams, underground water, and soils located close to the landfill. Heavy metals, such as zinc, lead, and mercury, can be found in these "juices" in greater concentrations than the ones permitted by law (Toro 1991, 1, 11). Section 503 of RCRA regulates the production of compost in the United States and Puerto Rico (Avilés 2002).

Besides the RCRA, other federal regulations that impinge on local management of waste are Part 256 of the Code of Federal Regulations, Title 40, Guidelines for the Development and Introduction of State Plans for the Management of Solid Residues (1965); Part 257 of the Code of Federal Regulations, Title 40, Criteria for the Classification of Solid Waste Installations and Practices (1979); and Part 258 of the Code of Federal Regulations, Title 40, Criteria for Solid Waste Landfills (1992) (ADS 2003, np).

Even though hazardous waste is out of the scope of this research, it has always been also an issue in the island. By 1985 Puerto Rico had already surpassed toxic waste generation projections. In 1985, the island already had generated 336,162 tons of toxic waste and projections forecast 269,000 tons per year by 2000 (Licha 1986, 5). The government does not know with certainty what type of toxic waste has been produced in the island, and where it has been disposed. Some environmental scientists, such as Cerame Vivas, have reported that almost all of the landfills in the island have received toxic or hazardous waste at some point in time, of course illegally (Fernández Colón 1988, 16). There has been a proposal for a hazardous material landfill in Ponce since the 1980s, but it never developed (Carrasco 1986a, 14). The only commercial toxic waste landfill that has operated in Puerto Rico is located in the municipio of Peñuelas. It has been closed for extended periods of time and fined by the U. S. Environmental Protection Agency and the Environmental Quality Board because it violated federal and state environmental laws (Carrasco 1986b, 5). The EPA has evaluated hundreds of potential Superfund sites and many are domestic landfills; e. g. (two in) Juncos, Barceloneta, Arecibo, Cidra, and Guayama. The spread of toxic material has gotten to a point that almost 100 percent of Puerto Rico's bodies of water are contaminated with a wide variety of carcinogens (Licha 1986, 5). Substances such as carbon tetrachloride, tricloroetilenous, and mercury have been found in water bodies (Licha 1986, 5).

Today there are twenty-nine operational landfills in Puerto Rico, including the ones located in the offshore islands of Vieques and Culebra, plus two transfer stations (and seven mini-transfer stations), one compost plant, and three MRFs in operation. There is other infrastructure that is not operational or that is privately owned that is not included in this analysis. The closure of numerous landfills in the last decade has meant a crisis from the stand point of waste management because this has been the primary method for waste disposal in Puerto Rico. However, waste management and disposal have been a threat to the environment and human health "forever" in Puerto Rico, even before the resurgence of public awareness during the last decades of the previous century. Today, the government and the people of Puerto Rico are dealing with the laxity and negligence that the government has dealt with this issue in the past. Furthermore, the preferred method of waste deviation, recycling, has not been put in effect effectively in the island. One of the biggest obstacles to implementing a recycling program has been citizen participation. Inadequate infrastructure and markets for recyclable material also contribute (ADS 2003, np). Municipal governments lack the economic resources to implement recycling programs, and to deal with solid waste management in general. Besides, many local governments see recycling as an additional program to the normal practices of waste collection and disposal, and with distinct solutions (ADS 2003, np). For these reasons, programs need more effective educational components and marketing campaigns have to be carried out through the schools, television, and radio, among others. The community-based approach, which was mentioned before in this chapter, could be put in practice. Mandatory recycling programs also can be effective (Tammemagi 1999, 48). In Puerto Rico recycling is voluntary. Today, as more landfills reach their life expectancies, less space is available for waste disposal, and greater amounts of generated waste can not find a disposal site. These events create today's waste crisis and the need for a redistribution of waste allocation across the island of Puerto Rico.

CHAPTER FIVE

ANALYSIS

The island of Puerto Rico has a total population of 3.8 million. It is a small island (approximately 39 by 111 miles) that is experiencing accelerated urban development, population growth, and consequently high population density. The population surge, in addition to governmental indifference and unplanned development, among other reasons, contribute to an unprecedented waste crisis. This problem intensifies in the most highly populated regions of the island, where most economic activities and the population are concentrated. Numerous landfills across the island have been closed, and many more are reaching their projected life expectancies. This is why this research intends to answer two main questions; how efficient is the present allocation and transportation of waste across the island of Puerto Rico, and how will waste be allocated by 2008, when there will only be ten operational landfills. Then the least-cost model developed for 2008 will be compared to a regional distribution that has been proposed by the ADS. Other waste-related infrastructure is also included in the analysis.

The present pattern of waste generators, disposal locations, and waste allocation is shown in Figure 5.1. The ADS has divided the island into four operational zones to manage the waste-related infrastructure (Figure 5.2). These zones are not self contained functional regions within the whole system. Municipios may use infrastructure located in zones outside of their own territory. An ADS technician is in charge of each zone and is supposed to visit it and evaluate its work and progress toward coping with the federal and local regulations. The first operational zone includes the east of the island, and contains twenty-one municipios (including Vieques and Culebra), eight landfills, two MRFs (one clean and one dirty), and two transfer stations. The second zone, which occupies most of the north-central and central region of the island, also contains twenty-one municipios, but contains seven landfills, one MRF, one mini-transfer station, and one compost center. The third zone includes the west region of the island, including part of the north-west and the south-west. It contains nineteen municipios, seven landfills, and four mini-transfer stations. The fourth operational zone extends throughout most of the south and south-east; it contains seventeen municipios, seven landfills, and two mini-transfer stations (Figure 5.2). The first operational zone provides service to the largest amount of population (1.4 million) and is the greatest generator in the island (3,016.5 tons/day). The second region contains a population of about 1 million and presents generation values of 2,481.4 tons/day. The third operational zone is the smallest region.

Even though today there are landfills spread all over the island, other waste-related infrastructure is not evenly distributed across the territory. For example, the only two transfer stations are located in a corner in the northeast; west-central and southern sections lack landfills and other waste facilities; and there is only one compost center located in the northwest. It appears that factors other than the regional set up and population distribution have determined the location of waste-related infrastructure in Puerto Rico. For example, community opposition has halted the siting of other compost centers and the government granted subsides and financial aid to private enterprises and individuals for the establishment of numerous MRFs, most of which did not survive for unknown and economical reasons (in many of these cases corruption has been suggested).

Table 5.1 details the distribution and allocation of waste for the main island, along with the values of demand and supply of municipios and landfills, respectively. The

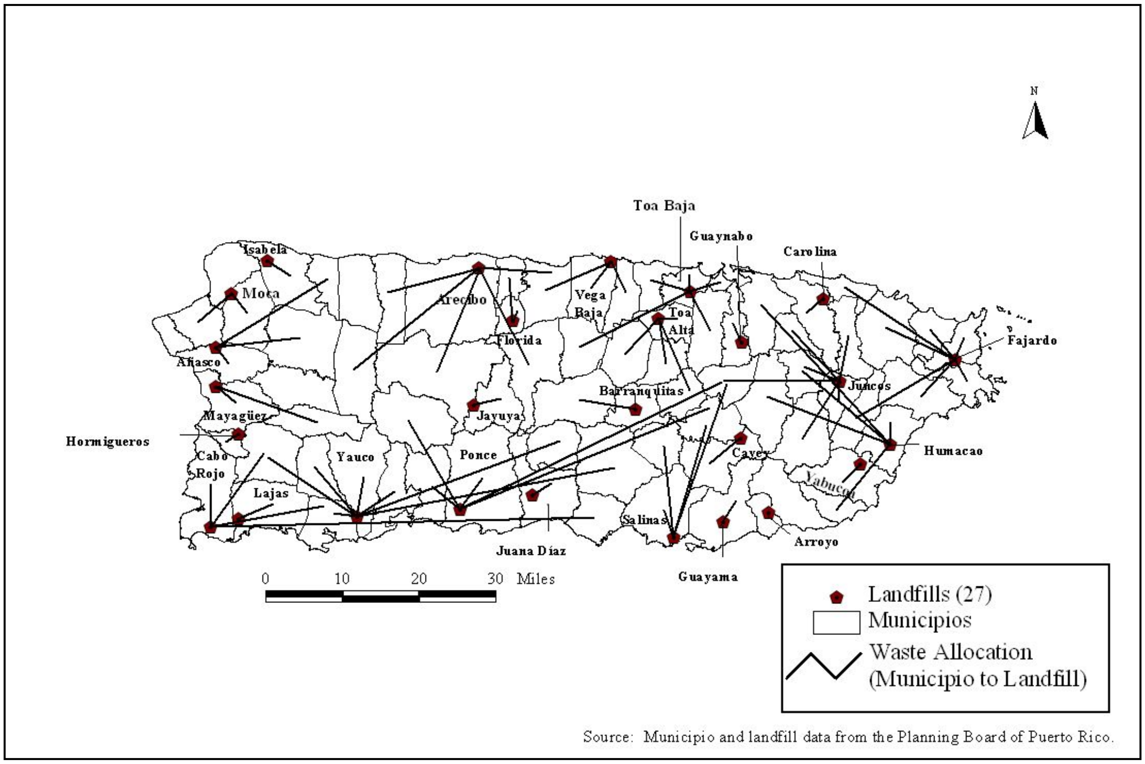


Figure 5.1 Present Pattern of Waste Generators, Disposal Locations, and Waste Allocation (2002)

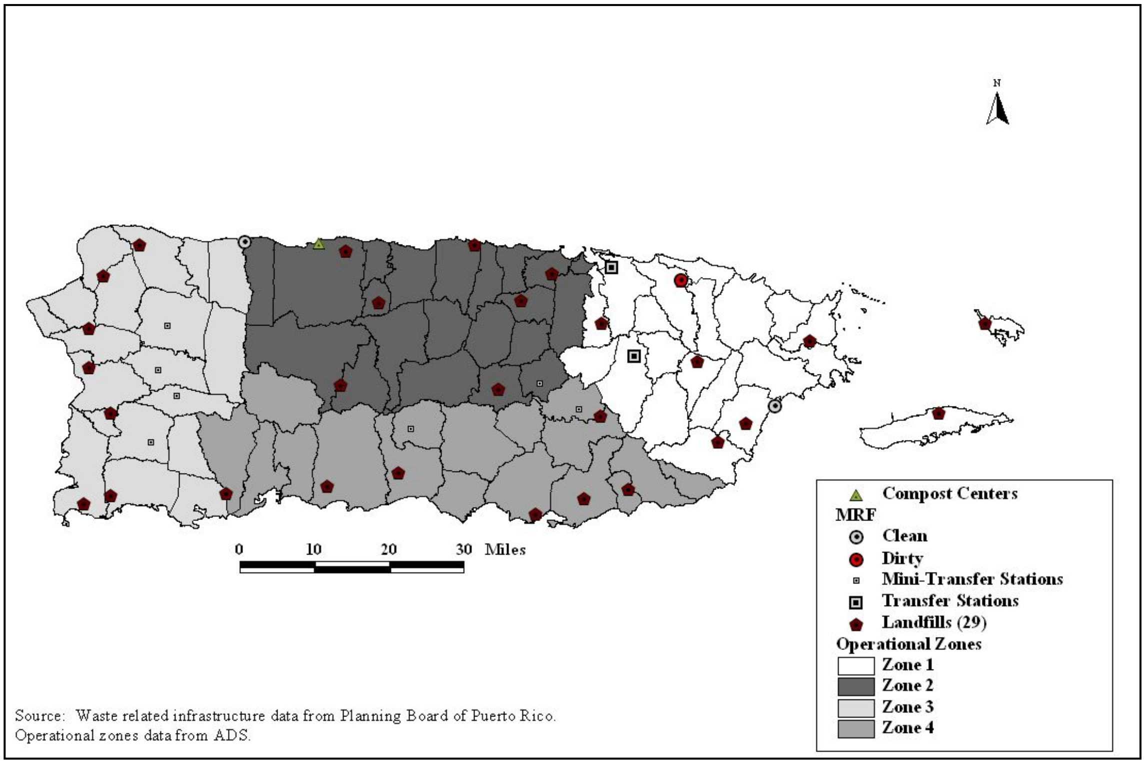


Figure 5.2 Operational Zones and Present Waste-Related Infrastructure (2003)

demand is the total number of tons that are generated per day by each municipio, representing the total service demand. Supply is the total landfill capacity in tons per day, and represents the total supply capacity available. At present, the total supply capacity of the twenty-seven landfills located in the main island is 12,967 tons/day, while the total demand of the municipios is 8,073.8 tons/day (Table 5.1 and Appendix A). Today some landfills receive larger amounts of waste per day than their capacity (Añasco, Cabo Rojo, Florida, and Juncos), which worsens the waste crisis because those landfills might reach their life expectancy before forecasted. It is important to emphasize that the values of the total population served that are presented in Table 5.1 are rough estimates because many municipios deposit their waste in more than one landfill, as well as some industries, MRFs, compost centers, and transfer stations. If the present location of disposal sites and allocation of waste is considered, municipios have to transport their waste a total of 1,122.8 miles, which represents a total cost (weighted distance) of 99,011.5 tons (miles) per day. The weighted distance is the product of the distance traveled times the demand, and it is a measure of the cost of the "commodity" flow.

Location-Allocation of the Present Landfills in Operation

Location-allocation was first performed in ArcInfo using the present availability of landfills to find out what would be the optimal distribution of waste according to their present location. For this analysis, there were twenty-seven supply points which are the landfills in operation and seventy-six demand points which are the centroids of the municipios located on the main island. The total demand of all the municipios is 8,073.77 tons/day and the total supply of the landfills is 12,967 tons/day (Table 5.1 and Appendix A).

Table 5.1 Present Patterns of Waste Generation, Landfill Capacity, and Waste Allocation (2002)

Landfill location	Population Served	Capacity (tons/day)	Life Expectancy (yrs)	Municipios that deposit (2003)	Demand (tons/day)	Distance (miles)	Weighted Distance miles(tons)/day
Añasco	98,002	150.0	8.0	Añasco	48.2	5.6	269.9
Añasco				Private Co.			0.0
Añasco				Quebradillas	35.0	31.4	1,099.9
Añasco				San Sebastián	70.9	18.5	1,311.7
Total	**98,002**	**150.0**			**154.1**	**55.5**	
Arecibo	274,027	850.0	6.5	Arecibo	209.0	10.9	2,278.3
Arecibo				Ciales	42.4	27.2	1,154.4
Arecibo				Hatillo	58.3	20.8	1,212.2
Arecibo				Lares	55.5	36.3	2,014.7
Arecibo				Manatí	69.3	12.2	845.1
Arecibo				Private Co.			0.0
Arecibo				Utuado	20.3	26.2	530.8
Total	**274,027**	**850.0**			**454.8**	**133.6**	
Arroyo	39,269	105.0	3.0	Arroyo	14.2	4.6	65.5
Arroyo				Patillas	9.7	5.6	54.1
Arroyo				Private Co.			0.0
Total	**39,269**	**105.0**			**23.9**	**10.2**	
Barranquitas	52,753	65.0	2.0	Barranquitas	20.4	0.8	16.3
Barranquitas				Orocovis	23.5	15.8	371.1
Barranquitas				Private Co.			0.0
Total	**52,753**	**65.0**			**43.9**	**16.6**	
Cabo Rojo	127,569	140.0	11.0	Cabo Rojo	65.3	2.5	163.3
Cabo Rojo				Guánica (partial)	25.9	20.0	517.8
Cabo Rojo				San Germán (some trips)	55.6	13.4	744.9
Cabo Rojo				Santa Isabel	48.6	61.0	2,965.2
Total	**127,569**	**140.0**			**195.4**	**96.9**	

(table cont.)

Landfill location	Population Served	Capacity (tons/day)	Life Expectancy (yrs)	Municipios that deposit (2003)	Demand (tons/day)	Distance (miles)	Weighted Distance miles(tons)/day
Carolina	186,076	900.0	2.0	Carolina	554.8	1.6	887.6
Carolina				Private Co.			0.0
Total	**186,076**	**900.0**			**554.8**	**1.6**	
Cayey	47,370	250.0	2.5	Cayey	66.8	3.4	227.2
Total	**47,370**	**250.0**			**66.8**	**3.4**	
Fajardo	221,670	346.0	6.5	Ceiba	7.7	3.3	25.5
Fajardo				Fajardo	117.4	3.4	399.0
Fajardo				Government Agencies			0.0
Fajardo				Las Piedras	22.9	23.5	538.4
Fajardo				Loíza	45.3	21.9	991.2
Fajardo				Luquillo	43.2	6.4	276.3
Fajardo				Naguabo	23.8	10.1	240.0
Fajardo				Private Co.			0.0
Fajardo				Río Grande	36.3	17.8	646.1
Total	**221,670**	**346.0**			**296.5**	**86.4**	
Florida	34,689	30.0	17.5	Barceloneta	96.8	6.8	658.5
Florida				Florida	19.3	0.3	5.8
Total	**34,689**	**30.0**			**116.2**	**7.1**	
Guayama	44,301	77.0	4.0	Guayama	48.7	6.1	296.9
Total	**44,301**	**77.0**			**48.7**	**6.1**	
Guaynabo	136,796	300.0	<1	Guaynabo	297.8	2.4	714.6
Guaynabo				Private Co.			0.0
Total	**136,796**	**300.0**			**297.8**	**2.4**	
Hormigueros	16,614	40.0	3.5	Hormigueros	27.2	0.8	21.8
Total	**16,614**	**40.0**			**27.2**	**0.8**	
Humacao	683,395	2,300.0	11.0	Caguas	334.5	21.1	7,057.5
Humacao				Gurabo	23.9	15.1	360.7
Humacao				Humacao	126.5	0.2	25.3

(table cont.)

Landfill location	Population Served	Capacity (tons/day)	Life Expectancy (yrs)	Municipios that deposit (2003)	Demand (tons/day)	Distance (miles)	Weighted Distance miles(tons)/day
Humacao				Maunabo	17.3	14.6	253.2
Humacao				Private Co.			0.0
Humacao				San Juan	1,041.5	31.1	32,391.3
Total	**683,395**	**2,300.0**			**1,543.8**	**82.1**	
Isabela	44,444	76.0	3.0	Isabela	72.1	2.4	173.1
Total	**44,444**	**76.0**			**72.1**	**2.4**	
Jayuya	17,318	58.0	1.5	Jayuya	21.6	4.2	90.8
Total	**17,318**	**58.0**			**21.6**	**4.2**	
Juana Díaz	50,531	200.0	2.0	Juana Díaz	68.5	2.1	143.9
Juana Díaz				Private Co. (Waste Management)			0.0
Total	**50,531**	**200.0**			**68.5**	**2.1**	
Juncos	262,287	315.0	1.5	Aguas Buenas (debris)	31.1	23.0	715.5
Juncos				Canóvanas	55.1	7.5	413.3
Juncos				Gurabo (partial)	23.9	5.1	121.8
Juncos				Juncos	150.3	4.5	676.2
Juncos				Private Co.			0.0
Juncos				San Lorenzo	36.6	15.7	575.2
Juncos				Trujillo Alto	44.8	13.7	613.3
Total	**262,287**	**315.0**			**341.8**	**69.5**	
Lajas	26,261	40.0	3.5	Lajas	39.8	7.7	306.3
Total	**26,261**	**40.0**			**39.8**	**7.7**	
Mayagüez	104,883	350.0	8.0	Maricao	9.2	24.0	220.8
Mayagüez				Mayagüez	273.1	5.3	1,447.2
Mayagüez				Private Co.			0.0
Total	**104,883**	**350.0**			**282.3**	**29.3**	
Moca	81,739	600.0	4.0	Aguada	49.1	27.5	1,350.8
Moca				Moca	48.2	4.4	211.9

(table cont.)

Landfill location	Population Served	Capacity (tons/day)	Life Expectancy (yrs)	Municipios that deposit (2003)	Demand (tons/day)	Distance (miles)	Weighted Distance miles(tons)/day
Moca				Private Co.			0.0
Total	**81,739**	**600.0**			**97.3**	**31.9**	
Ponce	304,122	1,200.0	8.0	Adjuntas	16.3	19.0	309.7
Ponce				Aguas Buenas (sometimes)	31.1	55.3	1,720.4
Ponce				Cidra (sometimes)	56.0	48.6	2,721.1
Ponce				Peñuelas	49.8	7.4	368.5
Ponce				Ponce	796.2	6.4	5,095.4
Total	**304,122**	**1,200.0**			**949.4**	**136.7**	
Salinas	129,391	417.0	8.0	Aguas Buenas	31.1	34.0	1,057.7
Salinas				Aibonito	24.6	21.2	521.1
Salinas				BFI (Service to Business)			0.0
Salinas				Cidra	56.0	27.5	1,539.7
Salinas				Salinas	34.5	7.7	265.3
Total	**129,391**	**417.0**			**146.1**	**90.4**	
Toa Alta	150,507	328.0	1.5	AAA			0.0
Toa Alta				BFI			0.0
Toa Alta				Comerío	5.3	17.4	91.7
Toa Alta				Corozal	20.0	9.0	179.6
Toa Alta				Naranjito	38.4	9.0	345.4
Toa Alta				Others			0.0
Toa Alta				Toa Alta	35.2	0.5	17.6
Total	**150,507**	**328.0**			**98.8**	**35.9**	
Toa Baja	412,182	2,500.0	1.5	Bayamón	467.3	7.9	3,691.8
Toa Baja				Cataño	521.5	6.4	3,337.9
Toa Baja				Dorado	86.2	4.2	362.1
Toa Baja				Morovis	10.6	23.9	254.1
Toa Baja				Private Co.			0.0
Toa Baja				Toa Baja	608.1	0.4	243.2

(table cont.)

Landfill location	Population Served	Capacity (tons/day)	Life Expectancy (yrs)	Municipios that deposit (2003)	Demand (tons/day)	Distance (miles)	Weighted Distance miles(tons)/day
Total	**412,182**	**2,500.0**			**1,693.8**	**42.8**	
Vega Baja	145,248	800.0	1.5	Manatí	69.3	9.2	637.3
Vega Baja				Private Co.			0.0
Vega Baja				Vega Alta	25.6	3.0	76.7
Vega Baja				Vega Baja	82.3	3.9	321.0
Total	**145,248**	**800.0**			**177.1**	**16.1**	
Yabucoa	39,246	105.0	1.5	Yabucoa	23.2	7.3	169.4
Total	**39,246**	**105.0**			**23.2**	**7.3**	
Yauco	219,894	425.0	11.0	Coamo	45.0	44.7	2,009.7
Yauco				Guánica	25.9	4.8	124.3
Yauco				Guayanilla	60.7	6.7	406.7
Yauco				Sabana Grande	40.2	10.6	426.5
Yauco				San Germán	55.6	15.2	845.0
Yauco				Villalba	48.7	57.2	2,786.2
Yauco				Yauco	85.7	4.6	394.1
Total	**219,894**	**425.0**			**361.8**	**143.8**	
Puerto Rico	**3,808,610**	**12,967.0**			**8,197.2**	**1,122.8**	**99,011.5**

(ADS 2002; ADS 2003, np; Quiñones, Diez, Silva and Associates and Brown and Caldwell 1995, TABLE A-1)

The first procedure carried out in ArcInfo was using the MINDISTANCE model. According to the results, waste would have to be transported a total distance of 629.23 miles by all the demand points to the supply centers, and the total weighted distance (cost) would be 49,775.6 (tons)miles per day. Even though distance is an important measure to determine the distribution pattern of waste allocation, in a real system of waste distribution this decision process is much more complex and other constraints are considered.

The second process employed was using the ALLOCATE command. Figure 5.3 illustrates how this system would work “ideally,” if distance and capacity were the only two elements that had to be taken into consideration to determine the allocation of waste to landfills (Table 5.2 and Figure 5.3). The ALLOCATE command uses a network, in this case a road network to assign flows within the system. The total distance traveled by all the municipios to deposit the waste was 733.68 miles, and the total cost (weighted distance) was 83,201.5 (tons) miles per day. Specifically, the municipio that had to send its waste the longest distance would be Lares (32.7 miles). The municipios that would be sending their waste the least distance are Humacao and Florida, because they would be depositing refuse in their own landfills. In theory, the municipio of Humacao will be traveling 0 miles to transport its waste to the landfill within its territory because this municipio’s centroid and landfill’s point fell almost on the same coordinates. In the case of Florida, its territorial size is so small that it is probably the municipio that will be transporting wastes the shortest distance. In general, the twenty-nine municipios that will be transporting waste the shortest distance will be depositing waste in the landfill within their territory or in a landfill in an adjacent municipio. If Figure 5.3 is evaluated, some municipios seem to transport their waste to far away landfills, while they pass by closer ones. For example, San Juan passes near by Junco's landfill in order to deposit in Humacao; Villalba, even though near by Juana Diaz's landfill, deposits in Salinas; and Lares trucks would travel all the way to Ponce's landfill. This is due to the fact that the ALLOCATE command considers landfill capacity in addition to distance. For example, San Juan, the greatest waste producer of the island, generates (1,041.5 tons/day) much more waste than what Juncos's landfill can receive, since it has a capacity of 315 tons/day. On the other hand, Humacao's landfill has a total capacity of 2,300 tons/day. This applies to the other two examples mentioned. The model developed is cost efficient taking into consideration distance, consumer's generation (municipio), and supplier's capacity (landfill). When the total distances yielded from the analysis using LOCATEALLOCATE and ALLOCATE commands is compared, it is apparent that distance increases when other factors, such as landfills' capacity, are included in the analysis.

When Figure 5.3 and Figure 5.1 are compared it is obvious that San Juan (which is the municipio that generates the largest volume of waste) still deposits its waste in the landfill of Humacao. Even though a distance impedance was not imposed when the allocation procedure was carried out, the waste allocation pattern obtained from this procedure presents shorter routes than the waste allocation patterns of the island today; i. e., under the "ideal" scenario, municipios tend to deposit their waste in the closest landfill available. It can also be observed that the allocation of waste from the least-cost model would bring savings to the system. The total distance and weighted distance of the model presented by the LA analysis are smaller than the present allocation of waste. Today

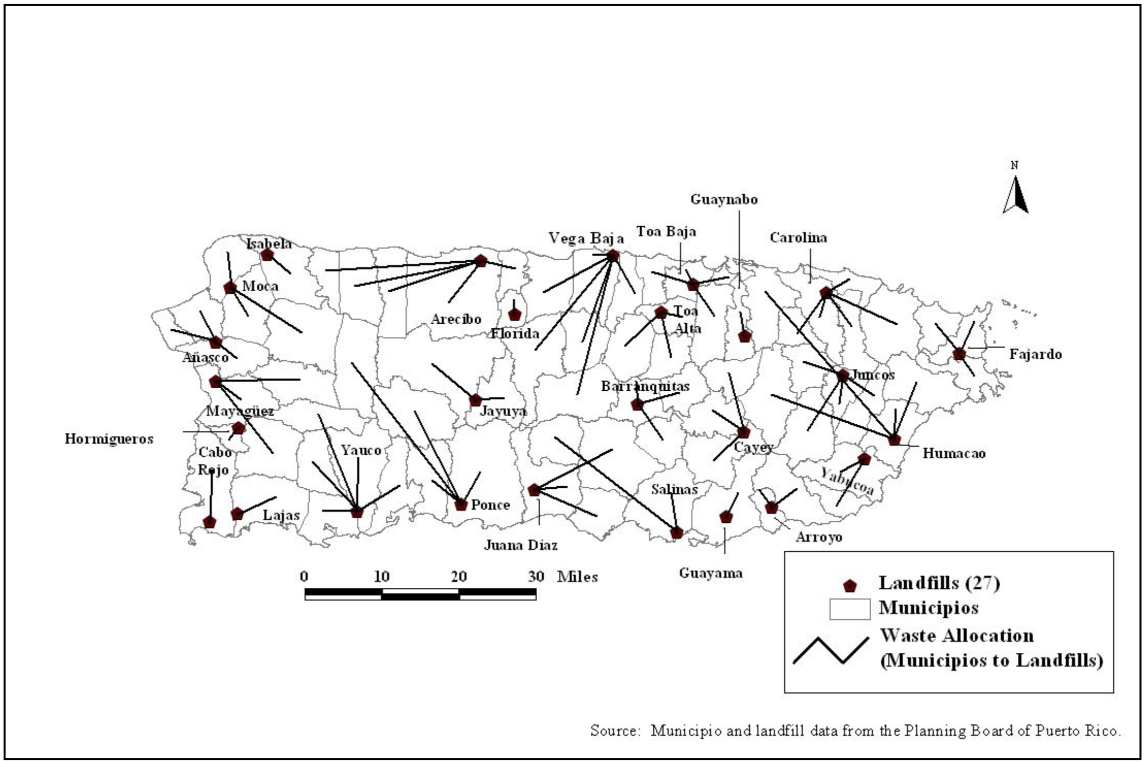


Figure 5.3 Least-Cost Model for Landfills Currently in Operation

municipios have to transport their waste a total distance of 1,122.8 miles with a cost of 99,011.5 tons (miles) per day, while under the model the total distance would be 733.68 miles and the weighted distance would be 83,201.5 tons (miles) per day. As will be explored later, these distributions will have to change and some municipios will possibly be depositing in landfills that are located farther away because this is a complex decision that is made up of many variables; e. g., transportation costs, tipping costs, and human resources, among others.

Location-Allocation of the Landfills with a Life Expectancy Less Than Five Years

If the present waste generation levels continue, waste recovery does not increase, and the landfills reach capacity when forecasted, by 2005 the waste generation will exceed the landfill capacity (Table 5.3 and Figure 5.4). This means that the ADS, the

Table 5.2 Pattern of Waste Allocation Under the Least-Cost Model (Landfills Currently in Operation)

Landfill Location	Supply (tons/day)	Municipios that Deposit	Distance (miles)	Demand (tons/day)	Weighted Distance miles(tons)/day
Añasco		Aguada	17.8	49.1	871.9
		Rincón	9.3	30.9	288.5
		Añasco	5.5	48.2	266.7
Total	**150**			**128.2**	
Arecibo		Barceloneta	4.6	96.8	441.5
		Camuy	20.2	37.6	758.1
		Quebradillas	24.5	35.0	859.4
		Hatillo	20.5	58.3	1,196.6
		Arecibo	10.6	209.0	2,209.4
Total	**850**			**436.7**	
Arroyo		Patillas	5.5	9.7	52.8
		Arroyo	4.5	14.2	63.9
Total	**105**			**23.9**	
Barranquitas		Comerío	11.7	5.3	61.4
		Barranquitas	0.7	20.4	15.0
		Aibonito	8.7	24.6	213.8
Total	**65**			**50.2**	
Cabo Rojo		Cabo Rojo	3.1	65.3	203.6
Total	**140**			**65.3**	
Carolina		Loíza	5.8	45.3	261.3
		Carolina	1.7	554.8	954.2
		Río Grande	10.0	36.3	362.5
		Trujillo Alto	12.4	44.8	555.2
		Canóvanas	5.9	55.1	322.5
Total	**900**			**736.2**	
Cayey		Aguas Buenas	16.9	31.1	525.2
		Cidra	10.5	56.0	586.8
		Cayey	3.9	66.8	257.5
Total	**250**			**153.9**	
Fajardo		Luquillo	6.2	43.2	265.9
		Fajardo	3.5	117.4	412.4
		Ceiba	3.0	7.7	22.9
Total	**346**			**168.3**	0.0
Florida		Florida	0.2	19.3	4.7
Total	**30**			**19.3**	0.0
Guayama		Guayama	5.5	48.7	269.1
Total	**77**			**48.7**	

(table cont.)

Landfill Location	Supply (tons/day)	Municipios that Deposit	Distance (miles)	Demand (tons/day)	Weighted Distance miles(tons)/day
Guaynabo		Guaynabo	2.5	297.8	739.4
Total	**300**			**297.8**	
Hormigueros		Hormigueros	0.7	27.2	19.1
Total	**40**			**27.2**	
Humacao		San Juan	30.9	1,041.5	32,231.0
		Naguabo	8.4	23.8	200.4
		Caguas	21.0	334.5	7,009.3
		Humacao	0.0	126.5	0.0
Total	**2,300**			**1,526.3**	0.0
Isabela		Isabela	2.3	72.1	167.2
Total	**76**			**72.1**	0.0
Jayuya		Utuado	10.0	20.3	202.1
		Jayuya	3.8	21.6	82.5
Total	**58**			**41.9**	0.0
Juana Díaz		Coamo	16.4	45.0	736.4
		Juana Díaz	2.3	68.5	156.8
		Santa Isabel	11.2	48.6	545.3
Total	**200**			**162.1**	
Juncos		Gurabo	4.8	23.9	113.7
		Juncos	4.3	150.3	645.9
		Las Piedras	6.7	22.9	153.0
		San Lorenzo	15.4	36.6	565.6
Total	**315**			**233.7**	
Lajas		Lajas	8.7	39.8	345.7
Total	**40**			**39.8**	
Mayagüez		Las Marías	17.1	9.6	164.3
		Mayagüez	5.3	273.1	1,441.1
		San Germán	14.5	55.6	805.3
Total	**350**			**338.3**	
Moca		Aguadilla	6.2	91.3	570.7
		Moca	4.6	48.2	220.7
		San Sebastián	13.5	70.9	954.4
Total	**600**			**210.4**	
Ponce		Lares	32.7	55.5	1,814.1
		Adjuntas	19.1	16.3	310.6
		Ponce	6.3	796.2	5,032.8
		Peñuelas	7.6	49.8	376.7
Total	**1,200**			**917.8**	

(table cont.)

Landfill Location	Supply (tons/day)	Municipios that Deposit	Distance (miles)	Demand (tons/day)	Weighted Distance miles(tons)/day
Salinas		Villalba	31.0	48.7	1,508.3
		Salinas	7.7	34.5	266.3
Total	**417**			**83.2**	
Toa Alta		Toa Alta	1.0	35.2	36.4
		Corozal	9.3	20.0	185.2
		Naranjito	9.3	38.4	356.8
Total	**328**			**93.5**	
Toa Baja		Cataño	6.7	521.5	3,477.1
		Dorado	4.4	86.2	380.3
		Toa Baja	0.6	608.1	375.9
		Bayamón	8.4	467.3	3,930.9
Total	**2,500**			**1,683.2**	
Vega Baja		Vega Baja	3.8	82.3	314.7
		Vega Alta	3.0	25.6	77.7
		Manatí	9.2	69.3	638.0
		Morovis	13.1	10.6	139.5
		Ciales	25.1	42.4	1,064.5
		Orocovis	28.4	23.5	667.2
Total	**800**			**253.7**	
Yabucoa		Yabucoa	7.3	23.2	168.5
		Maunabo	8.3	17.3	143.3
Total	**105**			**40.5**	
Yauco		Maricao	21.4	9.2	197.1
		Sabana Grande	10.5	40.2	424.5
		Yauco	4.8	85.7	412.2
		Guayanilla	6.8	60.7	414.4
		Guanica	4.5	25.9	115.9
Total	**425**			**221.7**	
Total	**12,967**		**733.4**	**8,073.8**	**83,201.5**

(ADS 2002; Quiñones, Diez, Silva and Associates and Brown and Caldwell 1995, TABLE A-1)

municipios, and other agencies will have to encourage other methods of waste reduction, will have to consider alternatives to landfilling, and will have to look at alternate landfills sites. This is why the location-allocation procedure was also carried out in a hypothetical scenario, considering only the landfills that are expected to remain open through 2008. By then, there will be around ten landfills open that will have a total supply capacity of

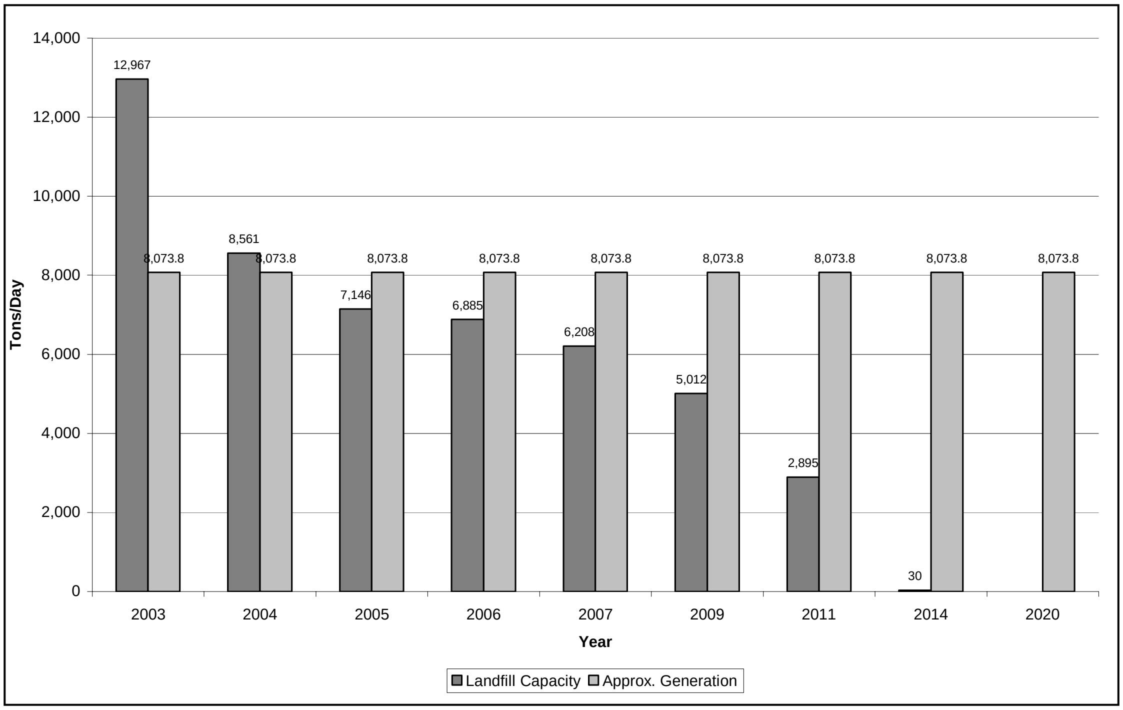
6,208 tons/day, and if the waste generation level stays about the same it will be around 8,073 tons/day. Figures 3.2 and 5.5 show that especially the central and the northeastern regions of the island will be lacking a disposal site by that date. Appendix C presents the projected values of waste generation for 2010 based on a projected 35 percent of waste reduction (Quiñones, Diez, Silva and Associates and Brown and Caldwell 1995, Table 2-1). The values used for this analysis were the same as for the previous analysis (for the present distribution of landfills) (Appendix A) because they appear more realistic than the projected values of waste generation for 2010, when it was presumed that the island would reach a 35 percent of reduction of waste through recycling. There are not enough criteria to determine what the waste generation volume will be for 2008, and since waste recovery levels have increased very slowly, it is not clear if they will reach 35 percent. Even if this total value of waste generation (7,350 tons/day) is compared to the landfill availability there will still be a crisis in waste management because the landfill space will be insufficient to meet the island's needs. Even though there is not enough supply to satisfy the demand, the location-allocation analysis was carried out to explore the possible waste distribution structure in the future.

Table 5.3 Comparison Between Landfill Capacity and Waste Generation (2003 – 2020)

Year	Landfill Capacity	Approx. Generation
2003	12,967	8,073.8
2004	8,561	8,073.8
2005	7,146	8,073.8
2006	6,885	8,073.8
2007	6,208	8,073.8
2009	5,012	8,073.8
2011	2,895	8,073.8
2014	30	8,073.8
2020	0	8,073.8

(ADS 2002; Quiñones, Diez, Silva, and Associates and Brown and Caldwell 1995, Table A-1)

For this analysis there were ten supply points (landfills available) and seventy-six demand points (centroids of the municipios). Using the MINDISTANCE model, the total distance traveled by the demand points was 1,351.5 miles. The total cost (weighted distance) was 169,313 (tons) miles per day.



(ADS 2002; Quiñones, Diez, Silva, and Associates and Brown and Caldwell 1995, Table A-1)

Figure 5.4 Waste Generation Versus Landfill Capacity (2003 – 2020)

In the previous analysis, the waste allocation was not done according to supply and demand capacity. The differences between the levels of waste generation and the landfill capacity that are expected by 2008 represent a problem from the start because the model is unable to allocate all of the waste that will be produced by that date. However, this analysis was performed to see how the waste could be distributed based on the alternative that the agencies in charge of waste management rely on the most right now, i.e., landfills. These results can also serve as a basis to carry out other analyses using other alternatives that the government and the municipios should consider further.

Using the ALLOCATE command, the waste of only seventy-two municipios was allocated to the landfills available. The municipios not included in the model's output were San Juan, Bayamón, Toa Baja, and Aguadilla, all of which have high population densities (Figure 5.5). The total allocated waste (of the demand points) was 5,865.5 tons/day. It is important to note that the total demand from all of the municipios is 8,073 tons/day, so by 2008 about 2,207.5 of the tons that will be generated per day will exceed landfill capacity (Table 5.4).

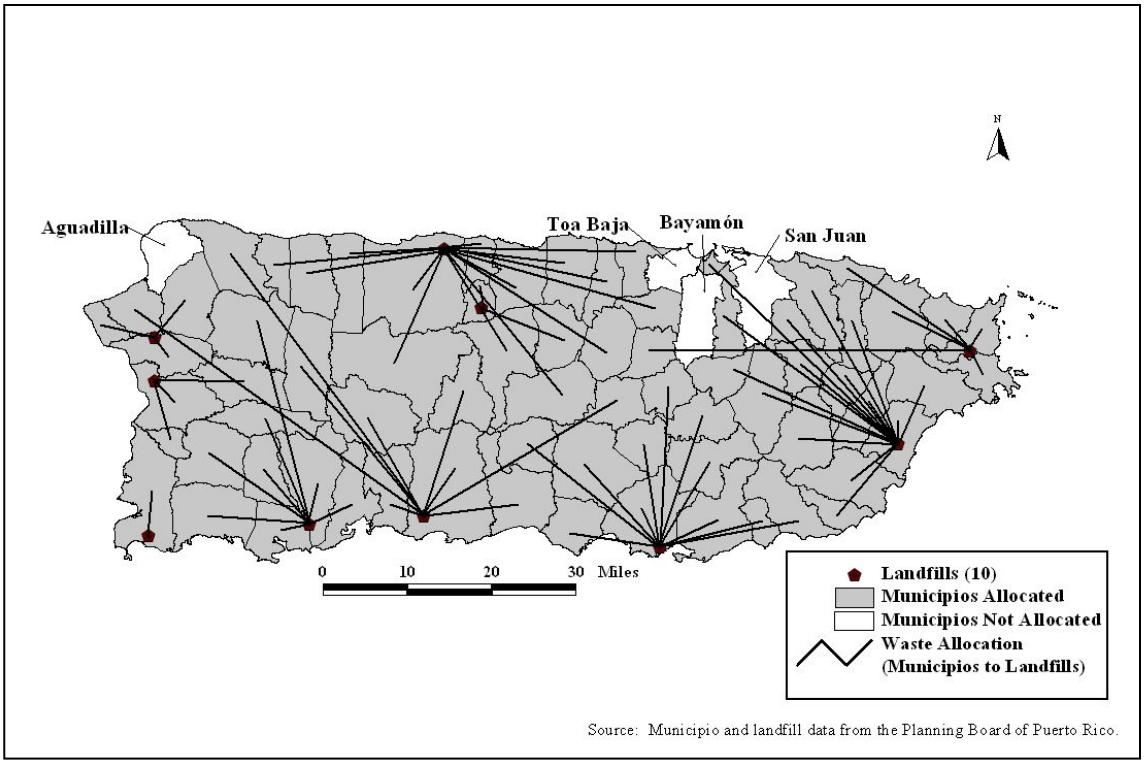


Figure 5.5 Least-Cost Model of Landfills (for 2008)

The outputs from the allocation procedure yielded a total distance of waste transport of 1,398.6 miles. The total weighted distance will be 110,848 tons (miles) per day. The municipio that will have to transport its waste the longest distance for disposal

Table 5.4 Pattern of Waste Allocation Under the Least-Cost Model (Landfills that will be Open for 2008)

Landfill Location	Supply (tons/day)	Municipios that Deposit	Distance (miles)	Waste Generation (tons/day)	Weighted Distance miles(tons)/day
Añasco		Moca	9.7	48.2	466.7
Añasco		Rincón	9.3	30.9	288.5
Añasco		Añasco	5.5	48.2	266.7
Total	**150**			**127.3**	
Arecibo		Barceloneta	4.6	96.8	441.5
Arecibo		Dorado	27.3	86.2	2,355.4
Arecibo		Camuy	20.2	37.6	758.1
Arecibo		Quebradillas	24.5	35.0	859.4
Arecibo		Vega Baja	16.0	82.3	1,318.6
Arecibo		Vega Alta	20.9	25.6	534.1
Arecibo		Hatillo	20.5	58.3	1,196.6
Arecibo		Manatí	12.5	69.3	867.5
Arecibo		Arecibo	10.6	209.0	2,209.4
Arecibo		Toa Alta	29.9	35.2	1,053.1
Arecibo		Corozal	28.6	20.0	570.6
Arecibo		Ciales	28.4	42.4	1,205.1
Arecibo		Utuado	25.9	20.3	524.8
Arecibo		Orocovis	38.5	23.5	903.2
Total	**850**			**841.4**	
Cabo Rojo		Cabo Rojo	3.1	65.3	203.6
Total	**140**			**65.3**	
Fajardo		Loíza	22.1	45.3	998.7
Fajardo		Luquillo	6.2	43.2	265.9
Fajardo		Río Grande	18.0	36.3	654.1
Fajardo		Fajardo	3.5	117.4	412.4
Fajardo		Naranjito	51.9	38.4	1,993.8
Fajardo		Ceiba	3.0	7.7	22.9
Total	**346**			**288.2**	
Florida		Florida	0.2	19.3	4.7
Florida		Morovis	22.7	10.6	241.8
Total	**30**			**30.0**	
Humacao		Cataño	35.7	521.5	18,610.7
Humacao		Carolina	28.3	554.8	15,679.0
Humacao		Guaynabo	28.4	297.8	8,468.4
Humacao		Trujillo Alto	23.7	44.8	1,059.1
Humacao		Canóvanas	20.7	55.1	1,139.9
Humacao		Gurabo	15.0	23.9	357.8
Humacao		Aguas Buenas	32.6	31.1	1,014.6
Humacao		Naguabo	8.4	23.8	200.4
Humacao		Caguas	21.0	334.5	7,009.3
Humacao		Juncos	9.3	150.3	1,391.4
Humacao		Las Piedras	6.9	22.9	157.6
Humacao		San Lorenzo	17.2	36.6	630.5
Humacao		Humacao	0.0	126.5	0.0

(table cont.)

Landfill Location	Supply (tons/day)	Municipios that Deposit	Distance (miles)	Waste Generation (tons/day)	Weighted Distance miles(tons)/day
Humacao		Yabucoa	14.4	23.2	333.8
Humacao		Maunabo	15.4	17.3	266.9
Total	**2,300**			**2,264.1**	
Mayagüez		Las Marías	17.1	9.6	164.3
Mayagüez		Mayagüez	5.3	273.1	1,441.1
Mayagüez		Hormigueros	9.0	27.2	244.9
Total	**350**			**309.9**	
Ponce		Isabela	69.7	72.1	5,030.0
Ponce		Aguada	66.2	49.1	3,250.5
Ponce		Lares	32.7	55.5	1,814.1
Ponce		Jayuya	26.6	21.6	575.0
Ponce		Barranquitas	41.4	20.4	842.7
Ponce		Adjuntas	19.1	16.3	310.6
Ponce		Juana Díaz	11.9	68.5	815.5
Ponce		Ponce	6.3	796.2	5,032.8
Ponce		Peñuelas	7.6	49.8	376.7
Total	**1,200**			**1,149.5**	
Salinas		Comerío	36.7	5.3	193.2
Salinas		Cidra	27.6	56.0	1,543.4
Salinas		Aibonito	21.7	24.6	533.4
Salinas		Villalba	31.0	48.7	1,508.3
Salinas		Cayey	22.1	66.8	1,475.8
Salinas		Coamo	18.4	45.0	829.3
Salinas		Patillas	21.4	9.7	206.7
Salinas		Guayama	12.4	48.7	605.9
Salinas		Salinas	7.7	34.5	266.3
Salinas		Santa Isabel	13.3	48.6	645.8
Salinas		Arroyo	13.0	14.2	185.1
Total	**417**			**402.0**	
Yauco		San Sebastián	43.6	70.9	3,094.2
Yauco		Maricao	21.4	9.2	197.1
Yauco		San Germán	15.2	55.6	847.4
Yauco		Sabana Grande	10.5	40.2	424.5
Yauco		Yauco	4.8	85.7	412.2
Yauco		Guayanilla	6.8	60.7	414.4
Yauco		Lajas	12.9	39.8	514.5
Yauco		Guánica	4.5	25.9	115.9
Total	**425**			**388.0**	
Total	**6,208**		**1,398.6**	**5,865.5**	**110,848.0**

(ADS 2002; Quiñones, Diez, Silva and Associates and Brown and Caldwell 1995, TABLE A-1)

will be Isabela, which would ship waste 69.77 miles to the landfill in Ponce. As in the previous analysis, the municipios that will have to transport the least distance will be

Humacao and Florida, which will deposit in the landfills located in their respective territories. In addition, many of the municipios that will transport the least distance will deposit their waste in landfills that are located within their territory or in adjacent municipios. It is also important to point out that as in the previous model (for the present distribution and location of landfills), some municipios transport waste to far away landfills. This is due to the fact that the ALLOCATE command takes demand and supply capacities into consideration in addition to distance, which will make some municipios travel further in order to deposit in landfills that have enough supply capacity. For example, Aguada and Isabela would transport their refuse to Ponce's landfill even though there are closer landfills.

Within five years most of the northeastern municipios (many of which are contained within the San Juan Metropolitan zone) will be depositing into the only two landfills remaining in the east (Humacao and Fajardo). Contrary to what the ADS expected, the landfills in the southern region will not have to provide service to the San Juan Metropolitan Zone and other northern municipios. However, it is important to remember that San Juan, Bayamón, and Toa Baja, which are among the highest volume waste producers on the island, will not have a disposal facility. Arecibo's landfill will be providing service to the rest of the northern section and parts of the central section of the island. The southern landfills will receive refuse mostly from municipios within their territory and the center of Puerto Rico. The same pattern applies to the three landfills that will remain open in the west (in Añasco, Mayagüez, and Cabo Rojo). Ponce's landfill will receive waste from distant municipios coming from the northwest and center of the island, such as Isabela, Aguada, and Barranquitas. By 2008 the center of the island will not have any landfills, assuming no new ones are created. The refuse coming from the center of the island will have to be deposited in landfills in other regions. The ADS predicted that within five years the waste generated in most of the north (including the northeastern metropolitan zone) would have had to be deposited in eastern, southern and western landfills (Maysonet 2002). However, according to the model obtained most of the refuse generated in these regions can be deposited in landfills within their territory and in the east. These results appear to have the potential of being more economically efficient because they allow for savings in transportation costs, infrastructure development, and human resources as compared to the ADS's original predictions.

Even though the results obtained from the LA procedure present a better scenario than what has been predicted by the ADS, the total distances and costs of transport of waste for 2008 are higher than those of the present allocation of waste and the model obtained from LA for the present landfills in operation (twenty-seven landfills). These results are expected due to the limited number of landfills that will be available by 2008. The total transport distances and cost for 2008's scenario would be 1,398.6 miles and 110,848 tons (miles) per day, respectively. On the contrary, the values for total transport distance and cost are 1,122.8 miles and 99,011.5 tons (miles) per day under the present allocation of waste; and 733.68 miles and 83,201.5 tons (miles) per day for the least-cost model with twenty-seven landfills available. The model that presents the highest savings of the three evaluated in this thesis (present allocation, least-cost model with twenty-seven landfills available, and least-cost model with ten landfills available) is the model obtained from LA for twenty-seven landfills available. These results suggest that by

2008 ADS should consider establishing landfills in empty areas, such as the center, in order to save on operating costs.

Present and Proposed Regional Distributions for Waste Management and Waste-Related Infrastructure (for 2008)

When the present operational zones are compared with the waste-related infrastructure that will be available for 2008, the east would have two landfills, two MRF (one dirty and one clean), and two transfer stations; the north would have two landfills, one mini-transfer station, one clean MRF, and one compost center; the west would have three landfills and four mini-transfer stations; and the south would have three landfills and two mini-transfer stations (Figure 5.6). As is the case today, it seems that within five years waste-related infrastructure would not be evenly distributed across the Puerto Rican territory. There would be clusters of the same kind of infrastructure in specific regions, while other regions would be lacking infrastructure. For example, there are only three MRFs on the island, two in the east and one in the northwest, and one compost center in the northwest. By this date this problem will be worsened by the decrease in available landfills. In addition, the center of the island has physical and human characteristics that set it apart from the rest of the island, and for this reason it should make up an independent region. Examples of its particular physical and human characteristics are its rugged topography and the low levels of population density. This is why this is an area that presents great challenges for the management of infrastructure in general, not only for waste management.

The ADS has proposed a reorganization of the island's established waste management regions. The new regional design would follow the so called "Five

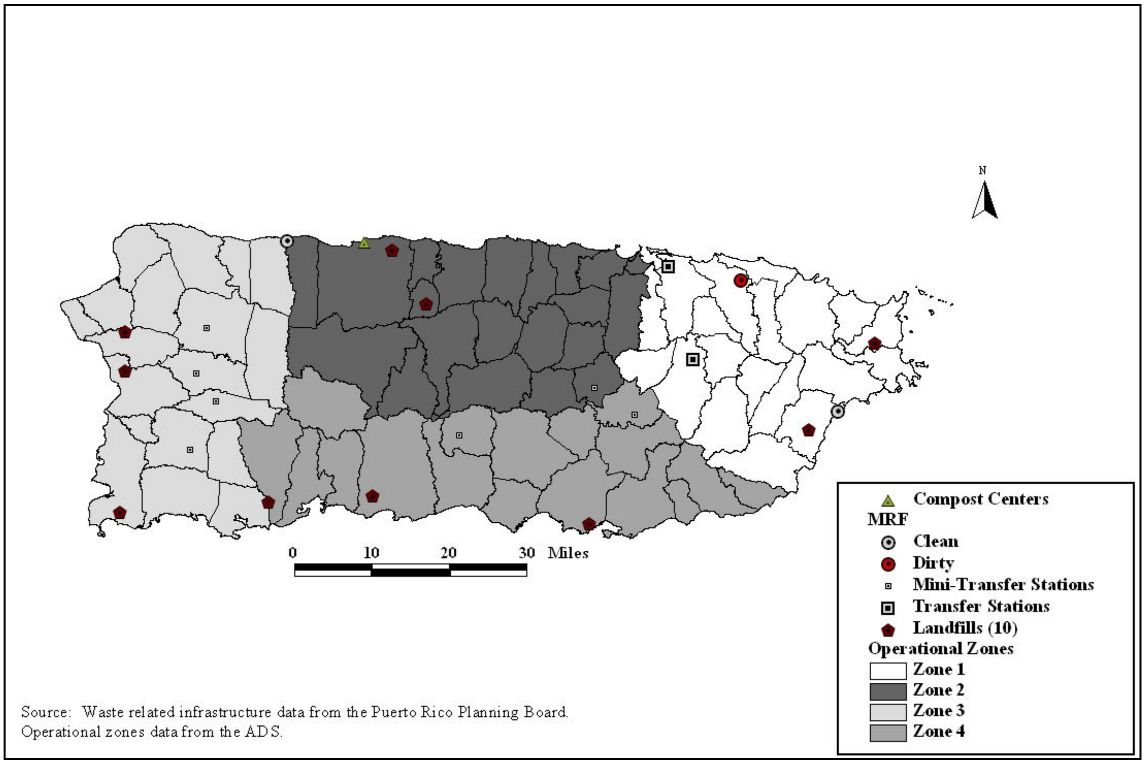


Figure 5.6 Operational Zones and Waste-Related Infrastructure (2008)

Development Poles" that are used by other governmental agencies to improve infrastructure development (ADS 2003, np). The eastern region would contain sixteen municipios, the south fourteen, the north sixteen, the west thirteen, and the center would have seventeen (Figure 5.7). Due to the population distribution, the region with the highest total population to be served will be the north with 1.4 million people, the second most highly populated region will be the east, and the regions with the least amount of people to serve will be the west and the south (Table 5.5). In terms of waste management infrastructure the eastern "development pole" will have two landfills, two MRFs (one dirty and one clean), and one transfer station by 2008; the south will have three landfills; the north will have two landfills (towards its west side), one transfer station, one compost center, and one MRF (clean); the west will have three landfills and four mini-transfer stations; and the center will have no landfills, but three mini-transfer stations (Figure 5.7).

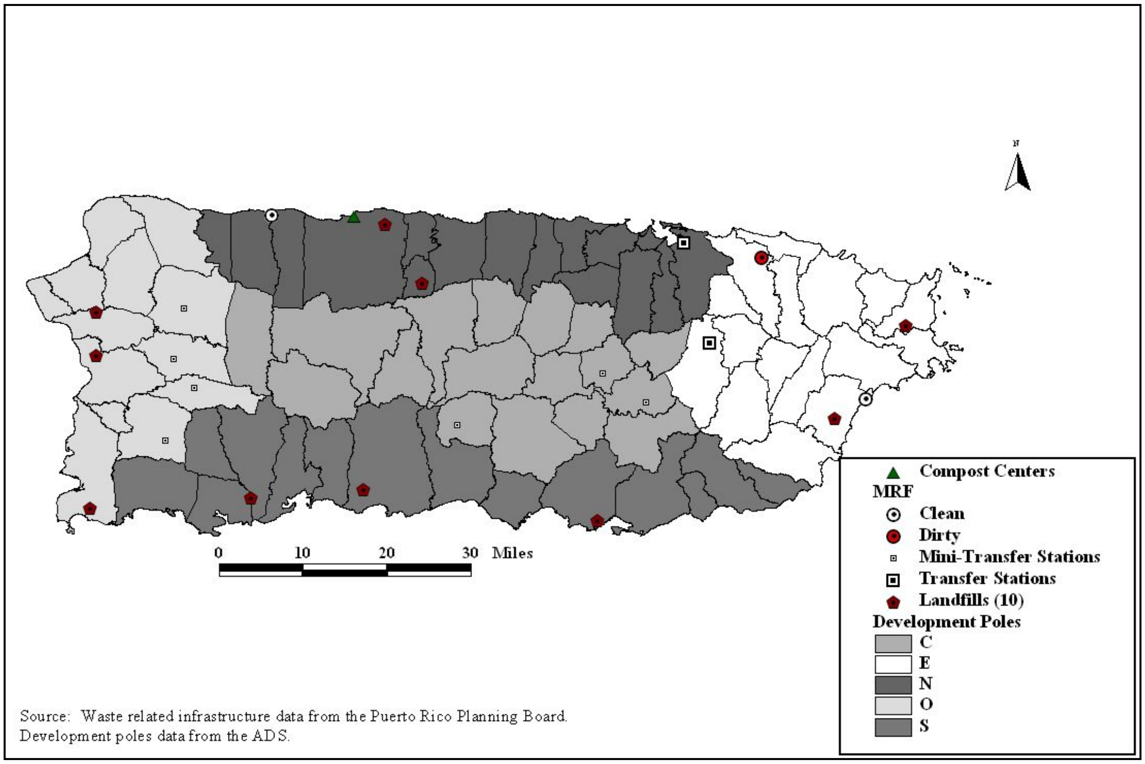


Figure 5.7 Development Poles and Waste-Related Infrastructure (2008)

As a result, the south will not have any waste disposal alternative available within its territory other than landfills, while the center will only have mini-transfer stations, but no landfill. If this regional distribution is established, the waste generation within most of the regions (except for the south and the east) will be greater than their landfill supply capacity (Table 5.5). However, due to the limited territorial extension of the island and the lack of landfill space, these regions will have to interact with each other in order to be able to cope with the generation levels; i. e. municipios from one region will have to use the infrastructure, including the landfills, located in another one. As it happens with the present distribution of infrastructure today, Figure 5.7 suggests that waste-related infrastructure will not be distributed evenly across the territory by 2008. For instance, the south will have only landfills within its territory, while the center of the island will not have landfills**,** but three mini-transfer stations in its eastern municipios. The west side of the central region lacks waste-related infrastructure.

Table 5.5 Development Poles, Generation Patterns, Population, and Supply Capacity of Landfills (for 2008)

Pole	Generation	Population	Number of Landfills	Supply Capacity of Landfills
Center	546.4	506,477	0	0.0
East	1,646.1	879,784	2	2,646.0
North	3,690.8	1,360,260	2	880.0
West	850.7	494,761	3	640.0
South	1,339.7	556,354	3	2,042.0
Total	8,073.8	3,797,636	10	6,208.0

(ADS 2003, np; ADS 2002; Quiñones, Diez, Silva, and Associates and Brown and Caldwell 1995, Table A-1)

Under the proposed regional make up each region would be made up of fewer municipios than the regional make up in use today. Since it segments the island in more regions, each one would contain less varied (waste-related) infrastructure. For instance, under the proposed regional make up for 2008 the south would only have landfills while under today's regional make up it would have landfills and mini-transfer stations. On the other hand, the "development poles" are used by numerous government agencies because each one of these regions have unique physical, economical, and industrial attributes that sets them apart, and treating them as independent regions simplifies their management. For example the north is a karst region made up of unique topography and physical characteristics that requires development strategies different from other areas; and the center possesses unique characteristics, such as its rugged mountainous topography and low population values. In addition, other government agencies use this regional set up to establish and plan infrastructure for Puerto Rico. This is why the use of the "development poles" appears to be an advantage for the ADS.

Proposed Distribution of Waste Management and the Least-Cost Model (for 2008)

If the waste management pattern developed using location-allocation and the proposed regions are compared, three of the greatest waste generators (San Juan, Bayamón, and Aguadilla) will not have a landfill to deposit their waste in (Figure 5.8). The municipios located in the eastern region will deposit their waste in the two landfills located in it. The San Juan Metropolitan Zone, in the northeast, will deposit its waste in the Humacao landfill, with the exception of Toa Alta, which will deposit in the landfill of Arecibo. Two of its largest generators, San Juan and Bayamón, will not have anywhere to deposit waste. The northern karst region (with the exception of the San Juan Metropolitan Zone) will be depositing its waste in the Arecibo landfill. The west will be depositing most of its waste in landfills located within its own region and in the south. The landfills in the southern region have more supply capacity than the ones in the west. The south, expect for Maunabo that will deposit in the landfill of Humacao, will have adequate capacity in the landfills that are inside its territory. Most of the center region's waste will be going to the landfills in the south, and the other part will be going to the northern landfills. There are only two municipios, Aguas Buenas and Naranjito, that will be depositing their waste in the east.

In terms of other infrastructure, most of the MRFs in operation have a capacity of 50 tons of waste per day, except for the one in Carolina that processes 300 tons per day (Appendix D). The San Juan transfer station processes an average of 1,250 tons per day, while the Caguas transfer station processes around 360 tons per day (Appendix E). In terms of the mini-transfer stations, they process around 43 tons a day, and the ones located in larger municipios tend to process higher volumes than the ones located in smaller ones (Appendix F). Finally, the only compost center in operation processes an average of 65 tons per day (Appendix G).

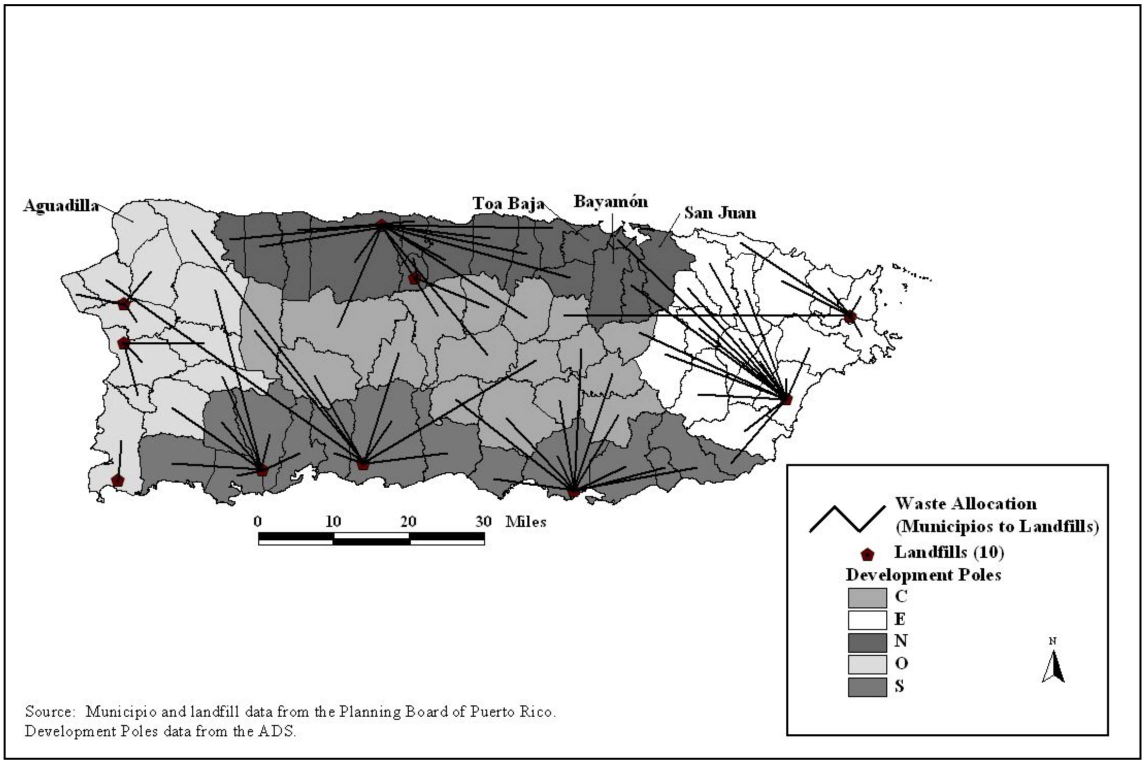


Figure 5.8 Development Poles and (LA) Least-Cost Model (for 2008)

The only dirty MRF in operation, located in Carolina, receives material only from Carolina. This facility will not have a nearby landfill in which to deposit its waste by 2008. The dirty MRF receives refuse that has not been separated (Quiñones, Diez, Silva, and Associates and Brown and Caldwell 1995, 3-61). The 1995 plan advised that it is better for these facilities to be located close to or adjacent to landfills, so they have a place to deposit the non-recyclable material. Within five years, the closest landfill to the Carolina MRF will be in Fajardo. Another option is that the MRF could transport the non-recyclable refuse to the transfer stations of San Juan or Caguas. Since this is the only dirty MRF in the island, and the only MRF in the northeast, the ADS could consider expanding the operations of this facility to let it receive waste from other eastern and northeastern municipios. Today it only receives refuse from Carolina. There are two clean MRFs, in Humacao and Hatillo (Figure 5.9). The Humacao MRF receives materials from municipios located in the eastern region; meanwhile, the Hatillo MRF receives material from municipios in the northern, central, and western region of the island. It is not clear how often and consistently this material is received from each of these municipios. The data provided by the ADS does not indicate where most of the municipios of the southern region, some in the center, and some in the San Juan Metropolitan Zone are taking their material, or if they are not taking their discards to any of the MRFs available (ADS 2003, np). Assuming the data is accurate, other operational MRFs (clean and dirty) are necessary, in order to provide service to the regions that are not making use of the open facilities.

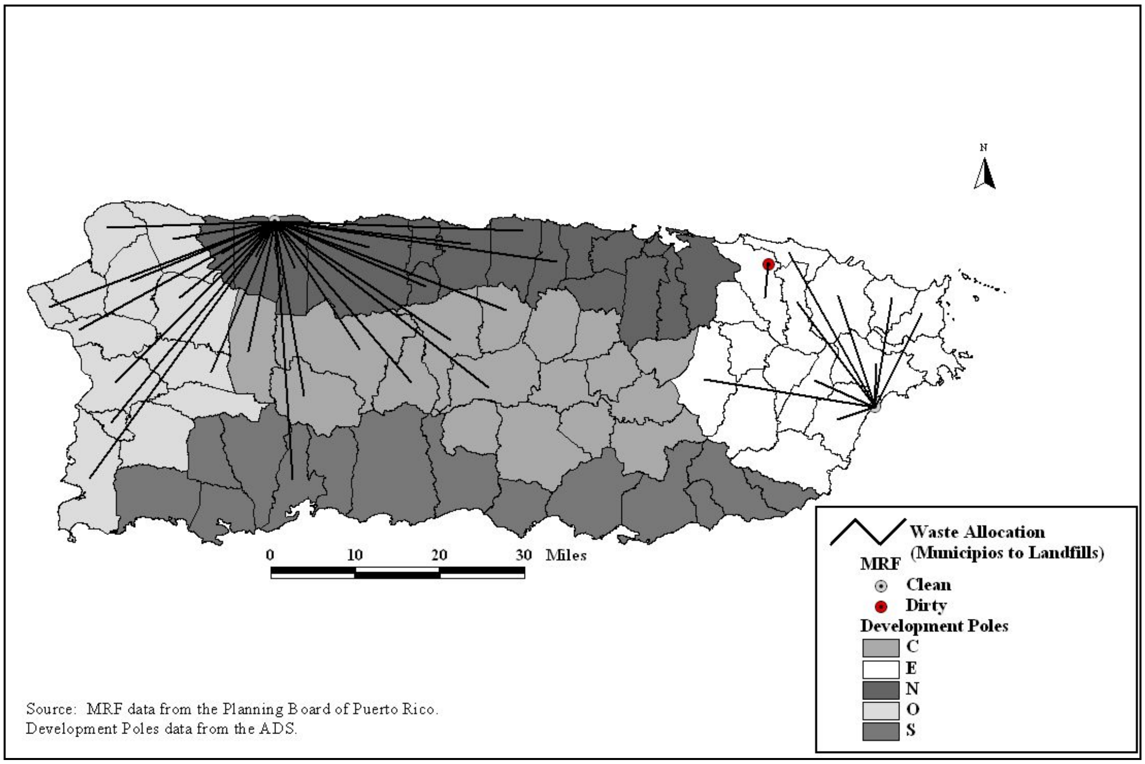


Figure 5.9 MRFs Location, Allocation of Refuse to this Facilities, and Development Poles Distribution

Most of the mini-transfer stations receive waste from the municipio in which they are located and deposit their refuse in landfills that are not necessarily the closest to their facility. The mini-transfer station of Las Marías deposits its refuse in the landfill of Aguadilla, which was not included in this research because it is temporarily closed (ADS 2003, np) (Figure 5.10). The two transfer stations of the island are located in Caguas and San Juan. They receive waste from the municipios in which they are located and both deposit their refuse in the Humacao landfill (Figure 5.10). Within five years some of these mini-transfer stations will have to redirect their waste to different landfills because the landfill that they deposit in today will be either closed or the least-cost model determined it more efficient to transport their material to another landfill. Examples of mini-transfer stations that will have to change their route are: San Sebastian's and Maricao's mini-transfer stations will have to deposit their waste in Yauco, Las Marías will have to ship to Mayagüez, Comerío will have to ship to Salinas, and Villalba's mini-transfer station will have to deposit in Salinas, among others (Figure 5.5 and Figure 5.10).

As can be observed, some of the western facilities will have to deposit their waste in southern landfills because they have more capacity than the western landfills. Additionally there need to be more mini-transfer stations put into operation in empty areas in the center of the island, and the transfer stations of Caguas and San Juan should expand their operations to be able to provide service to other northeastern municipios, or other transfer stations should be included in this and other sections of Puerto Rico (Figure 5.10). This is because transfer stations should be put in areas where the total distance traveled exceeds about 16 miles (25 Km) (Quiñones, Diez, Silva and Associates and Brown and Caldwell 1995, 3-60). Landfills that have already closed are ideal places for

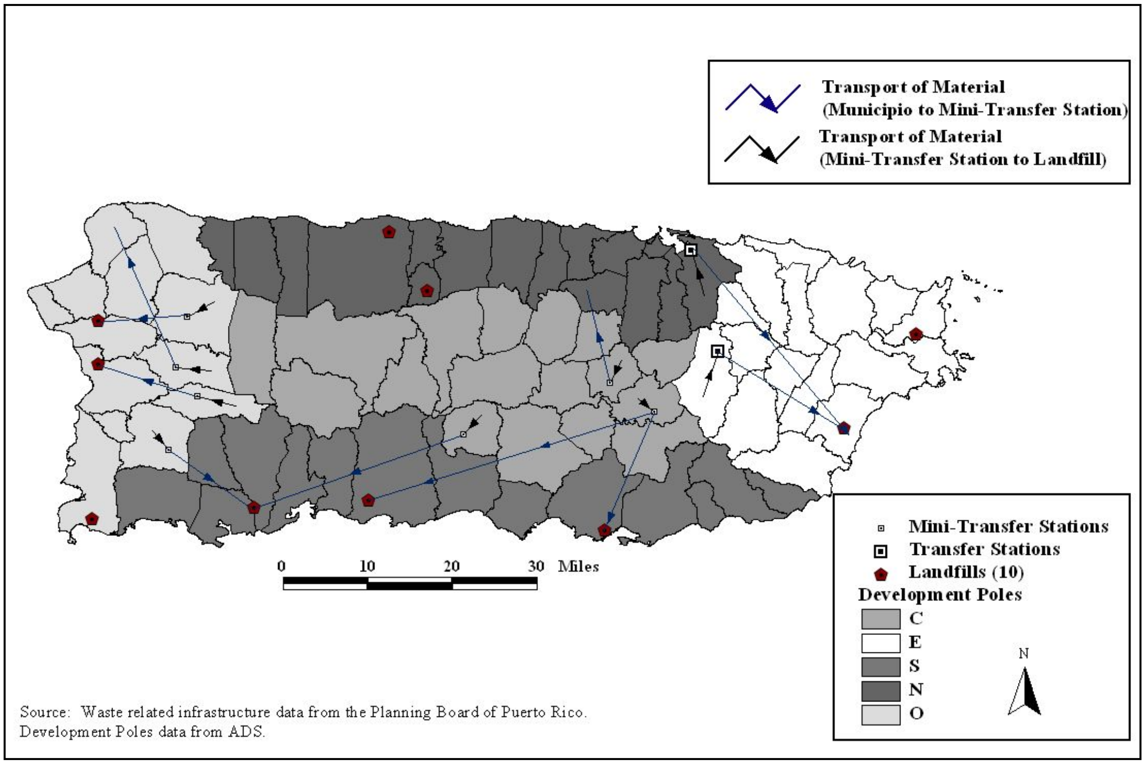


Figure 5.10 Distribution and Allocation of Waste for Mini-transfer Stations and Transfer Stations

the location of this kind of infrastructure (Quiñones, Diez, Silva, and Associates and Brown and Caldwell 1995, 3-61; ADS 2001a, np). For 2008 closed landfills, such as in Carolina, Guaynabo, Toa Alta, Toa Baja, and Juncos, can be turned into transfer stations, MRFs, or a combination that can provide service to areas such as the Metropolitan Zone of San Juan. As explained in the 1995 Plan, transfer stations should be located near clean MRFs so the material recovered from the blue bags and the drop offs can be transported to the latter facilities (Quiñones, Diez, Silva, and Associates and Brown and Caldwell 1995, 3-61). As can be observed in Figure 5.6 or Figure 5.7, this is not the case and shows that at least three other clean MRFs should be located in the northeastern, central, southern, and western regions. The data provided does not indicate in detail what municipios transfer their organic and vegetative refuse to the compost center of Arecibo. However, the ADS is considering establishing mini-compost centers for vegetative material. These facilities would be different from the compost center in existence now in Arecibo, which uses sludge from the water company's treatment plant to create compost (Quiles 2003). Other compost centers should be created across the island. They could be located in property associated with landfills either in operation or closed. The ADS should also consider that there are two compost centers (Jayuya and Toa Baja), five mini-transfer stations (Jayuya, Lares, Maunabo, Morovis, and Quebradillas), one transfer station (Barceloneta), and three MRFs (Guayanilla, Hormigueros, and Toa Baja) that are not in operation, but that are located in different regions of the island. This infrastructure may be open by 2008, but were not taken into consideration in this research

Other Considerations

As has been expressed before, the least-cost model developed in this research took into consideration only two constraints, distance, municipios' generation, and landfill supply capacity. On the other hand, waste management and the decision making of where to deposit waste is not solely determined by these two variables. A municipality will also have to consider the costs of transporting the waste to the landfill, which change depending on the distance, the place where it has to be taken, and the type of waste carried. An average of the transportation cost for domestic waste in Puerto Rico is $45 per ton (Calderón 2004). In addition, the place of generation also has to take in consideration the tipping cost, which averages $48.15 per ton in the island (ADS 2003, np).

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The island of Puerto Rico has a high population density, accelerated urban development, and rapid population growth that have and will continue to contribute to high per capita waste generation, especially in certain regions. The highest population densities are found, mostly, in the three economic nuclei: the Metropolitan Zone of San Juan, the city of Ponce, and the city of Mayagüez. But there is a population conglomeration in the northeast of the island on the area that makes up the Metropolitan Zone of San Juan. In contrast, the central mountain chain, the island-municipios of Vieques and Culebra, and areas of the south exhibit the lowest population densities. Waste generation, since it is related to the population density, is also higher in the economic nuclei. The municipality of Cataño has high total waste generation, despite its small size. On the other hand, Trujillo Alto and Toa Alta have high population density, but low values of per capita generation of waste. The total per capita waste generation calculated for the whole island is of 4.24 pounds per person per day.

The ADS has reported that there is an urgent need to distribute the waste management facilities efficiently and waste allocation cost-effectively (ADS ca2003, np; Maysonet 2002). This thesis sought a geographic solution to that problem. Two least-cost models were developed, for different scenarios, depending on the point in time and the levels of supply and demand that will be available. Currently, the total supply capacity from the twenty-seven landfills located in the main island is 12,967 tons/day. Meanwhile, the total demand from the municipios is 8,073.8 tons/day. If the total supply capacity of each landfill and the total waste that each one receives is compared, some of them receive more waste than their total daily capacity. This presents serious problems because these facilities will exhaust their capacity before current predictions.

The location-allocation analysis revealed that, when the distance parameter is the only constraint included (as was for the LOCATEALLOCATE phase), the total distance transported by all of the municipios would be shorter than when including other parameters such as capacity. In addition, it appears that under the model the municipios would transport their waste shorter distances, and deposit it in landfills that are closer to the source than what is seen today in Puerto Rico. If the total cost of the present allocation of waste is compared with the cost of waste allocation obtained from the model, the "ideal" distribution would be economically efficient and would represent savings to the system. The total cost of the present allocation of waste is 99,011.5 tons (miles) per day, while the cost under the "least-cost" model would be 83,201.5 (tons) miles per day. This shows that today's waste allocation is not necessarily efficiently distributed.

Figure 5.4 presents the alarming reality that by 2005 there will be more total demand in the island than total supply capacity and landfill space. Within five years there will be a total supply capacity from the landfills of 6,208 tons/day, and a total demand of 8,073.8 tons/day if the levels of waste reduction and recovery do not change. The least-cost model using the landfills that will be open within five years allocated only seventy-two of the seventy-six municipios located on the main island. The municipios that were not assigned to deposit in any landfill are in regions with high population densities. The total waste allocated was 5,865.5 tons per day. This means that there will be 2,207.5 tons generated daily above landfill capacity.

The northeast of Puerto Rico is one of the areas of major concern for the ADS because within five years it will not have landfills nearby in which to deposit its refuse (Maysonet 2002). The ADS predicted that by 2008 this area will have to deposit its refuse in landfills in the east, south, and even west of Puerto Rico (Maysonet 2002). However, the LA procedure generated a model which showed that most of the waste coming from this region could be transported to Humacao's landfill (in the east). Inadequate capacity there by 2008 suggests that San Juan, Toa Baja, and Bayamón (which are among the municipios with the highest waste generation) will not have facilities for refuse disposal. The rest of the north would be served mostly by Arecibo's landfill. These results appear to be more economically efficient than other possibilities considered by the ADS, because they allow for savings in transportation cost, human resources, and facility siting requirements. The municipios in the west would be depositing their waste in landfills in the southern and western regions. The center would deposit most of its waste in landfills located in the northern and southern regions. The southern landfills would be receiving refuse from central and southern municipios.

On the other hand, the scenario that presents the biggest savings is the model developed by LA for twenty-seven landfills available across the island. In contrast, the results from the LA for 2008 (when ten landfills will be available) provide better results than predicted by ADS, but the total distances values and cost are higher than the other scenarios evaluated in this thesis. The total transport distances and cost under 2008's scenario will be 1,398.6 miles and 110,848 tons (miles) per day, respectively. The values for total transport distance and cost are 1,122.8 miles and 99,011.5 tons (miles) per day under the present allocation of waste; and 733.68 miles and 83,201.5 tons (miles) per day for the ideal scenario with twenty-seven landfills available. This suggests that by 2008 ADS should consider establishing landfills in empty areas, such as the center, in order to save on operating costs.

A proposed regional realignment by the ADS was considered and compared to the least-cost model developed in this study. If this regional pattern is used, the northern and eastern development poles would serve the largest populations; and this would impact infrastructure needs. If the availability of infrastructure is compared to this proposed regional organization, only the south would have landfills, the center will host only mini-transfer stations, and the northeast will lack adequate infrastructure for waste disposal. In addition, within five years most of the regions will be facing greater demands than landfill capacity. All of these reasons indicate that the facilities will not be distributed evenly throughout the island. This is due, in part, to the fact that factors other than the regional set up and population distribution have determined the location of waste-related infrastructure in Puerto Rico.

Recommendations

In terms of other infrastructure, by 2008 the only dirty MRF located in Carolina (northeast) would have to take its refuse to the landfill of Fajardo or to the transfer stations of San Juan or Caguas. This facility should expand its operations to provide further services to the northeast and the east. The data obtained from the local agencies does not indicate where the northeast, the south, and parts of the center are taking their recyclable material. A possibility is that most of the municipios in these regions are not using the existent MRFs. This is why the agencies need to position more MRFs (clean and dirty) in empty regions, such as the south, the center, the west, and the northeast. Each region should contain at least one of these facilities.

The island's only two transfer stations are located in the northeast, and these two facilities need to expand their services. In addition, more are necessary in the other regions where municipios will be transporting waste longer distances. For example, the output shows that the municipios of Lares and Isabela will have to ship wastes more than 31.07 miles to deposit their refuse in Ponce. Another element that should be taken into consideration is that it is explained in the 1995 Plan that these structures should be located near clean MRFs so recovered material is taken to the latter facilities (Quiñones, Diez, Silva, and Associates and Brown and Caldwell 1995, 3-61), and this is not the case today in Puerto Rico. There should also be more mini-transfer stations in operation in sections of the center of the island. There is only one compost center in Puerto Rico, located in Arecibo. Community opposition has blocked the operation of a compost center that was constructed in Toa Baja's municipio. Infrastructure related to waste deviation is needed across the island, especially in the south. The properties where operational or closed landfills are located are ideal for the location of additional waste management infrastructure, and in that way the levels of the waste deposited could be reduced. The San Juan Metropolitan Zone has such high population density and high per capita waste generation that it should be set apart as a separate region making up most of the northeast. In this way, any plan developed by the ADS dealing with facility development and waste management would treat this zone as a separate region, and would therefore treat its unique economic, population, and infrastructure needs apart from any other area of the island. The same applies to the center of the island, whose unique physical and social attributes set it apart as a unique region, and it should be treated such as by the ADS.

Another element that needs urgent attention is the natural resources and communities that are being threatened today by the location of many of the landfills. Facility expansion in areas with threatened natural resources and communities should be seriously discouraged. Due to the obvious lack of landfill space the pertinent agencies should encourage reduction, reuse, and recycling, the use of other technologies, and the possible location of a landfill in the center of the island. An “integrated waste management” could be put into practice in which a variety of technologies are used while the impact on the environment is kept to a minimum (Tammemagi 1999, 33; McCoy 1996, 1).

Governmental agencies, and specifically the ADS, have to deal with serious issues of data management and data accuracy in order to be able to carry out real and long lasting improvements in waste management. Two important obstacles that have slowed and interfered with the development of governmental projects and programs are political indifference and the fanatical political party loyalties. The first one explains itself, but concerning the latter every time a new political party comes to power new secretaries and directors are put in power, and they do not continue the projects proposed or put in effect by the previous political administration. This does not allow for an effective and continuous solid waste management plan.

In this thesis I intended to solve a specific problem of the waste management process in Puerto Rico by developing an ideal waste allocation model (from the municipios to the landfills) under the current conditions and under future conditions (occurring by 2008) when more than half of the landfills will be closed. Even though this is a basic procedure in comparison to other LA extensions, to my knowledge this is the only research of this kind carried out on the island of Puerto Rico. This research is only the first step of a comprehensive study of distribution of solid waste, which could include other variables, such as the capacities of other infrastructure, the costs of transportation and tipping, and other steps of the process (such as collection and the reduction in weight and volume of waste in the transfer stations). In addition, more advanced LA procedures, such as hierarchical methods and transhipment models, could be used in order to include other constraints and bring other aspects of the process into the analysis. Further, once the future patterns of waste allocation are determined, the regions could be evaluated apart from each other, and using LA the new location of MRF, transfer stations, compost centers, and landfills could be determined. In addition, specific social, physical, and economic characteristics of each one of these regions would have to be analyzed in order to make the model developed more practical and realistic, while minimizing negative impact on environmental resources and human health.

This research demonstrates the usefulness and numerous applications of spatial analyses. More research needs to be carried out on the waste management issue in Puerto Rico, and the geographic discipline can contribute in numerous ways. Further research that uses varied statistical methods and Geographic Information Systems (GIS) software techniques is in great need and could help evaluate possible solution alternatives for the waste crisis. Furthermore, other perspectives, such as hazard studies, locational conflicts, environmental justice, and historical evaluations of this problem could be carried out in order to find underlying causes and historical events that have led the Puerto Rican nation to the crisis in which it is now immersed.

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APPENDIX A

PUERTO RICO'S TOTAL GENERATION, PER CAPITA GENERATION, AND TOTAL POPULATION

Name	Generation (tons/day) (1993)	Per Capita Generation (lb) (2000)	Population (2000)
Adjuntas	16.3	1.7	19,143
Aguada	49.1	2.3	42,042
Aguadilla	91.3	2.8	64,685
Aguas Buenas	31.1	2.1	29,032
Aibonito	24.6	1.9	26,493
Añasco	48.2	3.4	28,348
Arecibo	209.0	4.2	100,131
Arroyo	14.2	1.5	19,117
Barceloneta	96.8	8.7	22,322
Barranquitas	20.4	1.4	28,909
Bayamón	467.3	4.2	224,044
Cabo Rojo	65.3	2.8	46,911
Caguas	334.5	4.8	140,502
Camuy	37.6	2.1	35,244
Canóvanas	55.1	2.5	43,335
Carolina	554.8	6.0	186,076
Cataño	521.5	34.7	30,071
Cayey	66.8	2.8	47,370
Ceiba	7.7	0.9	18,004
Ciales	42.4	4.3	19,811
Cidra	56.0	2.6	42,753
Coamo	45.0	2.4	37,597
Comerío	5.3	0.5	20,002
Corozal	20.0	1.1	36,867
Dorado	86.2	5.1	34,017
Fajardo	117.4	5.8	40,712
Florida	19.3	3.1	12,367
Guánica	25.9	2.4	21,888
Guayama	48.7	2.2	44,301
Guayanilla	60.7	5.3	23,072
Guaynabo	297.8	6.0	100,053
Gurabo	23.9	1.3	36,743
Hatillo	58.3	3.0	38,925
Hormigueros	27.2	3.3	16,614
Humacao	126.5	4.3	59,035
Isabela	72.1	3.2	44,444
Jayuya	21.6	2.5	17,318
Juana Díaz	68.5	2.7	50,531
Juncos	150.3	8.2	36,452
Lajas	39.8	3.0	26,261
Lares	55.5	3.2	34,415

(table cont.)

Name	Generation (tons/day) (1993)	Per Capita Generation (lb) (2000)	Population (2000)
Las Marías	9.6	1.7	11,061
Las Piedras	22.9	1.3	34,485
Loíza	45.3	2.8	32,537
Luquillo	43.2	4.4	19,817
Manatí	69.3	3.1	45,409
Maricao	9.2	2.9	6,449
Maunabo	17.3	2.7	12,741
Mayagüez	273.1	5.5	98,434
Moca	48.2	2.4	39,697
Morovis	10.6	0.7	29,965
Naguabo	23.8	2.0	23,753
Naranjito	38.4	2.6	29,709
Orocovis	23.5	2.0	23,844
Patillas	9.7	1.0	20,152
Peñuelas	49.8	3.7	26,719
Ponce	796.2	8.5	186,475
Quebradillas	35.0	2.8	25,450
Rincón	30.9	4.2	14,767
Río Grande	36.3	1.4	52,362
Sabana Grande	40.2	3.1	25,935
Salinas	34.5	2.2	31,113
San Germán	55.6	3.0	37,105
San Juan	1,041.5	4.8	434,374
San Lorenzo	36.6	1.8	40,997
San Sebastián	70.9	3.2	44,204
Santa Isabel	48.6	4.5	21,665
Toa Alta	35.2	1.1	63,929
Toa Baja	608.1	12.9	94,085
Trujillo Alto	44.8	1.2	75,728
Utuado	20.3	1.1	35,336
Vega Alta	25.6	1.3	37,910
Vega Baja	82.3	2.7	61,929
Villalba	48.7	3.5	27,913
Yabucoa	23.2	1.2	39,246
Yauco	85.7	3.7	46,384
Puerto Rico	**8,073.8**	**4.2**	**3,808,610**

(Quiñones, Diez, Silva and Associates and Brown and Caldwell 1995, TABLE A-1; U.S. Census Bureau 2000)

APPENDIX B

MUNICIPIO'S TOTAL POPULATION AND POPULATION DENSITY

Name	Population (2000)	Pop Density (per square mile) (2000)
San Juan	434,374	9,084.4
Cataño	30,071	6,232.5
Bayamón	224,044	5,048.0
Carolina	186,076	4,105.1
Toa Baja	94,085	4,062.0
Guaynabo	100,053	3,688.3
Trujillo Alto	75,728	3,650.0
Caguas	140,502	2,394.6
Toa Alta	63,929	2,336.0
Aguadilla	64,685	1,767.8
Loíza	32,537	1,673.4
Ponce	186,475	1,625.5
Hormigueros	16,614	1,467.1
Dorado	34,017	1,458.2
Juncos	36,452	1,371.1
Vega Alta	37,910	1,366.1
Fajardo	40,712	1,362.9
Aguada	42,042	1,359.4
Vega Baja	61,929	1,349.5
Gurabo	36,743	1,319.7
Canóvanas	43,335	1,319.3
Humacao	59,035	1,318.6
Arroyo	19,117	1,271.0
Mayagüez	98,434	1,267.9
Barceloneta	22,322	1,196.5
Cidra	42,753	1,184.5
Quebradillas	25,450	1,123.6
Naranjito	29,709	1,094.1
Rincón	14,767	1,034.0
Las Piedras	34,485	1,017.7
Manatí	45,409	1,005.4
Aguas Buenas	29,032	949.8
Hatillo	38,925	931.6
Cayey	47,370	912.8
Corozal	36,867	865.7

(table cont.)

Municipio	Population (2000)	Pop Density (per square mile) (2000)
Río Grande	52,362	862.3
Aibonito	26,493	846.7
Barranquitas	28,909	844.8
Juana Díaz	50,531	838.1
Florida	12,367	813.9
Isabela	44,444	802.8
Arecibo	100,131	794.8
Moca	39,697	789.4
Villalba	27,913	787.5
San Lorenzo	40,997	771.4
Luquillo	19,817	771.2
Morovis	29,965	770.8
Camuy	35,244	759.1
Sabana Grande	25,935	722.7
Añasco	28,348	721.8
Yabucoa	39,246	710.3
Comerío	20,002	704.5
Guayama	44,301	680.8
San Germán	37,105	680.7
Yauco	46,384	680.6
Cabo Rojo	46,911	666.8
Santa Isabel	21,665	634.6
San Sebastián	44,204	627.2
Ceiba	18,004	619.9
Maunabo	12,741	605.6
Peñuelas	26,719	602.4
Guánica	21,888	589.8
Lares	34,415	559.9
Guayanilla	23,072	544.6
Coamo	37,597	481.7
Naguabo	23,753	459.4
Salinas	31,113	449.5
Lajas	26,261	436.9
Patillas	20,152	431.6
Jayuya	17,318	388.4
Orocovis	23,844	375.6
Utuado	35,336	311.5

(table cont.)

Municipio	Population (2000)	Pop Density (per square mile) (2000)
Ciales	19,811	297.2
Adjuntas	19,143	287.0
Las Marías	11,061	238.7
Vieques	9,106	179.2
Maricao	6,449	176.1
Culebra	1,868	160.8
Puerto Rico	3,808,610	1,112.1

(U.S. Census Bureau 2000)

APPENDIX C

WASTE GENERATION AND PER CAPITA WASTE GENERATION PROJECTIONS FOR 2010

Name	Waste Generation (tons/day) (2010)	Per Capita Waste Generation (lb) (2010)	Population (2000)
Adjuntas	27.0	2.8	19,143
Aguada	63.0	3.0	42,042
Aguadilla	117.0	3.6	64,685
Aguas Buenas	40.0	2.8	29,032
Aibonito	43.0	3.2	26,493
Añasco	40.0	2.8	28,348
Arecibo	203.0	4.1	100,131
Arroyo	33.0	3.5	19,117
Barceloneta	37.0	3.3	22,322
Barranquitas	40.0	2.8	28,909
Bayamón	610.0	5.4	224,044
Cabo Rojo	67.0	2.9	46,911
Caguas	370.0	5.3	140,502
Camuy	53.0	3.0	35,244
Canóvanas	70.0	3.2	43,335
Carolina	470.0	5.1	186,076
Cataño	120.0	8.0	30,071
Cayey	87.0	3.7	47,370
Ceiba	33.0	3.7	18,004
Ciales	27.0	2.7	19,811
Cidra	73.0	3.4	42,753
Coamo	57.0	3.0	37,597
Comerío	30.0	3.0	20,002
Corozal	53.0	2.9	36,867
Dorado	67.0	3.9	34,017
Fajardo	77.0	3.8	40,712
Florida	17.0	2.7	12,367
Guánica	33.0	3.0	21,888
Guayama	63.0	2.8	44,301
Guayanilla	30.0	2.6	23,072
Guaynabo	270.0	5.4	100,053
Gurabo	63.0	3.4	36,743
Hatillo	63.0	3.2	38,925
Hormigueros	30.0	3.6	16,614
Humacao	110.0	3.7	59,035
Isabela	60.0	2.7	44,444
Jayuya	20.0	2.3	17,318
Juana Díaz	67.0	2.7	50,531
Juncos	67.0	3.7	36,452

(table cont.)

Name	Generation of Waste (tons/day) (2010)	Per Capita Generation of Waste (lb) (2010)	Population (2000)
Lajas	37.0	2.8	26,261
Lares	40.0	2.3	34,415
Las Marías	13.0	2.4	11,061
Las Piedras	53.0	3.1	34,485
Loíza	83.0	5.1	32,537
Luquillo	33.0	3.3	19,817
Manatí	60.0	2.6	45,409
Maricao	3.0	0.9	6,449
Maunabo	17.0	2.7	12,741
Mayagüez	253.0	5.1	98,434
Moca	53.0	2.7	39,697
Morovis	40.0	2.7	29,965
Naguabo	33.0	2.8	23,753
Naranjito	43.0	2.9	29,709
Orocovis	27.0	2.3	23,844
Patillas	30.0	3.0	20,152
Peñuelas	37.0	2.8	26,719
Ponce	373.0	4.0	186,475
Quebradillas	30.0	2.4	25,450
Rincón	13.0	1.8	14,767
Río Grande	110.0	4.2	52,362
Sabana Grande	40.0	3.1	25,935
Salinas	43.0	2.8	31,113
San Germán	57.0	3.1	37,105
San Juan	1,027.0	4.7	434,374
San Lorenzo	60.0	2.9	40,997
San Sebastián	60.0	2.7	44,204
Santa Isabel	23.0	2.1	21,665
Toa Alta	113.0	3.5	63,929
Toa Baja	193.0	4.1	94,085
Trujillo Alto	143.0	3.8	75,728
Utuado	47.0	2.7	35,336
Vega Alta	80.0	4.2	37,910
Vega Baja	113.0	3.6	61,929
Villalba	33.0	2.4	27,913
Yabucoa	67.0	3.4	39,246
Yauco	70.0	3.0	46,384
Puerto Rico	**7,350.0**	**3.9**	**3,808,610**

(Quiñones, Diez, Silva and Associates and Brown and Caldwell 1995, TABLE 2-1; U.S. Census Bureau 2000)

APPENDIX D

MRFs IN OPERATION

Instalation	Status	Owner	Operator	Estimated Capacity (ton/day)	Type of residue that processes	Usuary	Final Disposal
Carolina	In Operation	Municipio	Landfill Technologies	300	Dirty recyclable material	Carolina	Carolina
Hatillo	In Operation	Fomento	Corporación Reciclaje del Norte, Inc. PT	50	Clean recyclable material	Arecibo	To Sell
						Hatillo	
						Florida	
						Manatí	
						Camuy	
						Utuado	
						Lares	
						Quebradillas	
						Morovis	
						Vega Alta	
						Ciales	
						Vega Baja	
						Aguadilla	
						Adjuntas	
						Moca	
						San Sebastián	
						Isabela	
						Añasco	
						Cabo Rojo	
						Rincón	
						Las Marías	

(table cont.)

Instalation	**Status**	**Owner**	**Operator**	**Estimated Capacity (ton/day)**	**Type of residue that processes**	**Usuary**	**Final Disposal**
						Orocovis	
						Mayagüez	
						Hormigueros	
						Juvenile Detention C.	
						Guayanilla	
						Jayuya	
Humacao	In Operation	Fomento	GC Reciclaje, Inc., PT (GC Recycling, Inc. PT)	50	Clean recyclable material	Humacao	To Sell
						Las Piedras	
						Caguas	
						Naguabo (by contract)	
						Canóvanas	
						Río Grande	
						Loíza	
						Culebra	
						Fajardo	
						ADS	
						Luquillo	

(ADS 2003, np)

APPENDIX E

TRANSFER STATIONS IN OPERATION

Operator	Estimated Capacity (ton/day)	Type of residue that processes	Usuary	Final Disposal
Waste Management	1,000 - 1,500	Domestic, debris	San Juan, Waste Management	Humacao
Waste Management	340 - 375	Domestic, debris and recyclable material	Caguas, Waste Management	Humacao, to sell

(ADS 2003, np)

APPENDIX F

MINI-TRANSFER STATIONS IN OPERATION

Instalation	Status	Owner	Operator	Estimated Capacity (ton/day)	Type of residue that processes	Usuary	Final Disposal
Cidra	In operation	ADS	BFI	70	Domestic	Cidra, Aguas Buenas	Salinas, Ponce
Comerío	In operation	ADS	Municipio	30	Domestic	Comerío	Toa Alta
Las Marías	In operation	ADS	Municipio	10	Domestic	Las Marías	Aguadilla (provitional)
Maricao	In operation	ADS	Municipio	10	Domestic	Maricao	Mayagüez
San Germán	In operation	ADS	Municipio	80	Domestic	San Germán	Yauco
San Sebastián	In operation	ADS	Municipio	60	Domestic	San Sebastián	Añasco
Villalba	In operation	ADS	Municipio	40	Domestic	Villalba	Yauco

(ADS 2003, np)

APPENDIX G

COMPOST CENTER IN OPERATION

Instalation	Status	Owner	Operator	Estimated Capacity (ton/day)	Type of residue that processes	Usuary	Final Disposal
Arecibo	In operation/ in expansion	ADS	Caribbean Composting, Inc	50 - 80	Vegetative material, wood, sludge	Comunities and Treatment Plant AAA	To sell

(ADS 2003, np)

VITA

Sandra A. Soto Bayó was born and raised in Río Piedras, Puerto Rico. An interest in environmental topics led her to geography. She studied at the University of Puerto Rico, Río Piedras, where she earned a bachelor of arts degree in geography. During her undergraduate studies she worked on research concerning coastal erosion in the island of Caja de Muertos, Ponce, Puerto Rico. Even though during her years as a graduate student she moved away from coastal studies, topics of environmental awareness still permeate in her research work.